SHORELINE EROSION STUDY
NORTH SOLANA BEACH, CALIFORNIA

Prepared for
SOLANA BEACH COASTAL
PRESERVATION ASSOCIATION
c/o Mrs. Ann Baker
219 Pacific Avenue
Solana Beach, California 92075

Prepared by
GROUP DELTA CONSULTANTS, INC.
San Diego, California

Project No. 1831
August 20, 1998

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Geotechnical Engineering
Geology
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Environmental Engineering

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Dear Mrs. Baker:

In accordance with your request, Group Delta Consultants, Inc has completed an evaluation of shoreline erosion currently affecting the coastal bluffs within the northern portion of Solana Beach in Northern San Diego County, California. The study area includes the northerly 4,000" feet of coastline starting at the northerly city limits and extending south to the Las Brisas Condominium complex just south of Fletcher Cove. This report has been prepared to address both the geotechnical and coastal aspects relevant to shoreline erosion and to provide a technical basis for any proposed shoreline and coastal bluff protection, consistent with Chapter 17.62 of the Solana Beach Municipal Code.

The accompanying report presents the results of our field investigative work, our review of available historical aerial photographs, maps and literature, the available methodologies used to assess the rates of coastal erosion, and our basis for evaluating the variations in future coastal erosion that would affect the Solana Beach coastline.

We appreciate the opportunity to work with you on this project. If you have any questions or require additional information, please give us a call.

Very truly yours,
GROUP DELTA CONSULTANTS, INC.

Walter F. Crampton, Principal Engineer
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WFC/PCB/jc
Attachments

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SHORELINE EROSION STUDY
NORTH SOLANA BEACH, CALIFORNIA

1 INTRODUCTION

1.1 Purpose and Scope

This report documents the variations in shoreline erosion susceptibility in the Solana Beach area of San Diego County (Figure 1). Storms in recent decades have removed beaches, and major bluff failures have occurred during the 1997-98 El Niño storm season along this portion of the coast, giving rise to uncertainty about future bluff stability and rates of bluff retreat. This report addresses the likely variations in bluff retreat and measures to mitigate future retreat.

Coastal retreat is a geomorphic process that has operated for thousands of years and continues today. In evaluating both long-term and short-term geomorphic processes along the Solana Beach coastline, this report initially identifies the available methods of coastal retreat analysis, ranging from a critique of historical documents and photographs, to the application of appropriate geomorphic and soil-profile dating methods. It then compares long-term geologic rates of coastal erosion over thousands of years with more recent rates, which are to a great degree influenced by anthropic (human) activities. Next, it applies these various methods and levels of coastal bluff analyses to specific reaches of the Solana Beach coastline to provide estimates of current and future rates of coastal retreat. Finally, it identifies an option for mitigation.

1.2 Location

The Study area encompasses approximately 4000 feet of shoreline extending from the south edge of Cardiff State Beach at the northerly city limits of the City of Solana Beach to the south property line of Las Brisas Condominiums (Las Brisas), located just south of Fletcher Cove.

2 PHYSIOGRAPHY AND GEOLOGY

The Solana Beach coastline extends from the south side of San Elijo Lagoon approximately 1.4 miles south to the projection of Via De La Valle, the southern city limits. The coastal bluffs extend southerly an additional 0.3 mile to the San Dieguito River valley. This reach of coastline consists of steep coastal bluffs, except at Fletcher Cove. The bluffs range in height from approximately 70 feet at Cardiff State Beach, to 90 feet south of Las Brisas. San Elijo Lagoon is the discharge point for the significant drainage of Escondido Creek extending 20 miles to the east. The San Dieguito River valley extends approximately 70 miles into the back country to the crest of the Laguna Mountains. The canyon at Fletcher Cove naturally drains the area of the City between Pacific Coast Highway and the coastal bluff. A large storm drain also discharges at the Cove. Low altitude oblique aerial photographs and accompanying topographic maps (Photo and Map Nos. 1 through 8, respectively) depict the general character of the study area.

Prior to the establishment of extensive residential development along the bluff top, the drainage divide of the coastal terrace was formed by an ancient beach ridge typically 50 feet back from the contemporary bluff-top, thus limiting over-bluff discharges to very localized runoff. Southerly of 525 Pacific Avenue, the terrace surface slopes away from the bluffs, preventing any over bluff discharge. Development has not modified the natural drainage pattern, except within individual residential lots. With the exception of a few of the northerly lots, the residences along the bluff are built at elevations above street elevation. Consequently, drainage from lots is almost entirely to the street. Backyards of a few of the northerly lots are below the adjacent street level and, at these locations, a small amount of surface drainage discharges over the bluff to the beach. Similarly, backyards of a few of the southerly lots appear to have indefinite drainage, suggesting that locally, a small amount of backyard runoff southerly of 525 Pacific Avenue may also discharge over the bluff.

Overbluff drainage discharges are minimal at Solana Beach compared to the coastal bluffs in Encinitas (the adjacent coastal community to the north). In Encinitas, the top of the ancient beach ridge is upwards of 500 feet east of the bluff top, large areas of ponding and over-bluff discharge occur, exacerbating subaerial erosion processes in that coastal community. Given the topography of the coastal bluff top within the study area portion of Solana Beach, natural subaerial erosion processes are less active compared to the majority of San Diego County's upper sloping coastal bluffs, and therefore the coastal bluffs along Solana Beach will tend to sustain a steeper upper-bluff profile.

2.1 Geologic Site Conditions

Geologic units present in the Solana Beach area include the older Eocene "bedrock" geologic units that form the lower cliffed portion of the bluffs and the late Pleistocene marine terrace deposits that form the sloping, upper coastal bluffs above the sea cliffs (Kennedy and Peterson, 1975).

2.1.1 Eocene-Age Seacliff-Forming Units

Two Eocene-age geologic units are exposed, in order of increasing age, from south to north along the Solana Beach coastline: the Torrey Sandstone and the Delmar Formation. The approximate areal extent of these relatively resistant, cliff-forming geologic units is shown on the eight photographs and accompanying maps.

Torrey Sandstone: The Torrey Sandstone is a well-indurated, white-gray to light yellow-brown, medium- to coarse-grained sandstone. The lower portions of the Torrey Sandstone contain bioturbated beds and concretions, while the upper portions exhibit high-angle cross-bedding (Kennedy and Peterson, 1975).

Delmar Formation: The Delmar Formation is a moderately well-indurated, yellow-green and olive-gray, sandy claystone interbedded with medium gray, coarse-grained sandstone exposed in the lower portion of the sea cliff northerly of 633 Pacific Avenue. This geologic unit also comprises the more erosion resistant offshore reefs within the northerly portion of the city. Abundant well-cemented oyster beds exist within this geologic unit, substantially contributing to its erosion resistance and also responsible for the presence of Tabletop reef extending some distance offshore (Kennedy and Peterson, 1975).

2.1.2 Pleistocene-Age Bluff-Forming Units

Bluff-forming units overlie a wave-cut abrasion platform formed on the Eocene bedrock approximately 120,000 years ago when sea level was 20 feet higher (Lajoie and others, 1992). At the time, the sea was at a high eustatic level due to substantial melting of the ice caps during an interglacial period. Today, the abrasion platform ranges in elevation from approximately 18 feet near San Elijo Lagoon, to approximately 26 feet at Las Brisas. The difference in elevation is a result of variable regional uplift associated with gentle tectonic folding during the last 120,000 years.

Terrace Deposits: The sloping, upper portion of the Solana Beach bluffs is comprised of predominantly late Pleistocene, moderately-consolidated, poorly-indurated, light reddish-brown, silty fine sands that include both nearshore marine and beach sands lithologically similar to the Bay Point Formation (approximately 120,000 years old).

“Beach Ridge” Type Deposits

The terrace deposits are typically capped by an iron oxide-cemented “beach ridge” type residual clayey sand deposit. This erosion-resistant cap material, formed by the concentration of clayey weathering products, secondary oxides of iron and aluminum, and leached and reprecipitated salts, is the result of long exposure to the elements during a period of tropical to temperate climate.

Pleistocene-Age Canyon Fill

Fletcher Cove is bounded on the north and south by the walls of an ancient stream valley filled by Quaternary-age alluvium, talus and marine estuary sediments. This infilled stream valley pre-dates the deposition of the overlying Bay Point Formation (approximately 120,000 years old). As a cliff-forming geologic unit, this material is more erodible than the adjacent Torrey Sandstone and, hence, has allowed approximately 80 feet of differential erosion beyond that of the more linear coastal bluff forming what is today Fletcher Cove.

It should also be noted that the depression in the coastal bluff in this area, i.e., within the upper terrace surface, represents an excavation made in the late 1920s to provide a visual and recreational amenity in this North County community, and is not of geologic or geomorphic origin. Prior to the excavation, however, this area did originally drain to the coastal bluff, with its small upland watershed extending easterly to Pacific Coast Highway.

2.1.3 Groundwater

Although limited amounts of groundwater likely exit the coastal bluffs in this area, the topographic relief, with upwards of 20 feet of fall from the coastal bluff to Pacific Coast Highway, and then ample gradient to San Elijo Lagoon to the north and Fletcher Cove to the south, likely limits the volume of initial infiltration as a groundwater source. Additionally, unlike the more impervious Eocene formations further north, the underlying Torrey Sandstone does not create an impermeable perching horizon, which would encourage groundwater to exit the bluff face along the contact between the coastal terrace deposits and the underlying cliff-forming Eocene-age formation. Although surfacing groundwater is often a problem within other North County coastal areas, the Solana Beach coastline appears to be relatively immune to this subaerial process, with the possible exception of the Pleistocene fluvial deposits underlying Fletcher Cove. Typical sources of groundwater would include: 1) natural groundwater migration from highland areas to the east of the terrace, and 2) infiltration of the terrace surface by rainfall, and by agricultural and residential irrigation waster (Turner, 1981). During our field investigative work, groundwater was only observed at the back of the sea cave below 205 Pacific Avenue and along the Pleistocene contact within Fletcher Cove, where it may have contributed to the increased differential marine erosion in this area.

2.2 Geologic Structure

The geologic structure of the Solana Beach coastline is the result of faulting and folding in the current tectonic regime, which began approximately 5,000,000 years ago when the Gulf of California began to open in association with renewed movement on the San Andreas fault system (Fisher and Mills, 1991). The nearest member of the fault system is the Rose Canyon fault zone running approximately parallel to the coast, two to three miles offshore. Movement along the fault appears to have caused gentle folding on the coastal side of the fault. The gentle folding has caused a small southeast dip in the Eocene-age formations, thus exposing progressively older formations northerly along the coast. In more recent times, the 120,000-year-old wave-cut abrasion platform has been tilted to the northwest at about 0.1 degree.

Tectonic forces are also evident in the localized folding and faulting of the Eocene-age sediments. The episodes of faulting and long-continued tectonic stresses have resulted in hundreds of visible joints, fractures and shear zones having both micro- and large-scale variations in erosion potential. Several of the sea caves, most notably northerly of Tide Park, formed along these Pleistocene age faults where fractures and shear zones allow differential erosion and the propagation of a sea cave along the axis of the fault. Fault-induced sea caves southerly of Tide Park are limited to those below Las Brisas and 231 Pacific Avenue; however, most of the sea caves northerly of Tide Park are fault-controlled. Faulting has also juxtaposed the Delmar Formation against the Torrey Sandstone below 633 Pacific Avenue with the Delmar Formation upthrust against the Torrey Sandstone and likely contributing to the presence of Tabletop Reef just to the north.

2.3 Coastal Bluff Geomorphology

2.3.1 Terminology for the Bluff and Adjacent Shore

The geomorphology of a typical coastal-bluff profile is shown in Figure 2. The Figure shows the shore platform, a lower near-vertical cliffed surface called the seacliff, and an upper bluff slope generally ranging in inclination between 35 and 65 degrees (measured from the horizontal). The bluff top is the boundary between the upper bluff and the flat to gently sloping coastal terrace.

Offshore from the seacliff is an area of indefinite extent called the nearshore zone (see Figure 2). The bedrock surface in the nearshore zone, which extends out to sea from the base of the seacliff, is the shore platform. Worldwide, the shore platform may vary in inclination from horizontal, to a gradient of three horizontal to one vertical, or 33- percent (Trenhaile, 1987). Offshore from Solana Beach, the gradient of the shore platform ranges from approximately one to two percent. The boundary between the seacliff (the lower, vertical and near-vertical section of the bluff) and the shore platform is called the cliff-platform junction, or shoreline angle. Photo Nos. 9 and 10 (Blackburn collection), taken from just south of Tide Park on December 12, 1997, during a -1.2 foot MLLW tide, show the gently seaward sloping bedrock shore platform denuded of sand with minor erosion channeling extending up to the differentially eroded seacliffs. Photo No. 11 (Folger collection) shows Tabletop Reef and the shore platform within the northern portion of the study area.

Within the nearshore zone is a subdivision called the inshore zone, beginning where the waves begin to break (Figure 2). This boundary varies with time because the point at which waves begin to break is a function of wave height, tidal level, and sand level. During low tides, large waves will begin to break far out to sea. During high tide, waves may not break at all, or they may break directly on the lower seacliff. Closer to shore is the foreshore zone, that portion of the shore lying between the upper limit of wave wash at high tide and the ordinary low water mark. Both of these boundaries usually lie on a sand or shingle beach. The foreshore zone is not designated on Figure 2, since the transient shingle/beach deposits are not shown. More importantly, insufficient sand beach exists today to support the backshore, or elevated beach, which typically remains dry and defines the landward edge of the foreshore. Thus, at Solana Beach, the foreshore extends to the sea cliff and allows waves, on a daily basis, to impact directly upon, and actively erode, the coastal bluff.

2.3.2 Classification of Bluff Geometry

Assessing the rate of coastal retreat requires an understanding of the dynamic relationship between the upper bluff and seacliff. Emery and Kuhn (1982) developed a global system of classification of coastal bluff profiles, and applied that system to the San Diego County coastline from San Onofre State Park to the southerly tip of Point Loma. In their regional study, the Solana Beach area is designated as Type “C (c)” (see Figure 3). The letter “C” designates coastal bluffs having a resistant geologic formation at the bottom, and less resistant materials in the upper parts of the bluff. The relative effectiveness of marine erosion of the lower resistant formation, compared to subaerial erosion of the upper bluff, produces a characteristic profile. Rapid marine erosion compared to subaerial erosion produces a steep overall bluff, whereas slower marine erosion produces a more gently-sloping upper bluff. The letter "(c)" indicates that the long-term rate of subaerial erosion is approximately equal to that of marine erosion. Where the upper-bluff terrace deposits are undergoing active subaerial erosion, the slope face is slightly concave. Where subaerial erosion is less active, it is slightly convex.

Local geologic variations within the study area create a derivative of the Type "C(c)" bluff. The geologic sections along the Solana Beach coast show a partially-cemented cap of beach ridge sediments. In these areas, where the cap erodes more slowly and protects the underlying uncemented sediments, the upper bluff will retreat more in accordance with the Type "B(c)" bluffs in the Emery and Kuhn classification, maintaining a steeper profile.

2.4 Shoreline Processes

Littoral currents (currents running parallel to the beach) are one of the dynamic factors affecting the entire North County coastline. Littoral current is set in motion by waves moving toward the beach at an angle. Such waves have perpendicular and parallel components relative to the beach. Under such conditions, sand grains that are lifted by the surf are moved at right angles to the beach, and at the same time, they are transported down the beach with the littoral current.

Solana Beach is located within the southern portion of the Oceanside Littoral Cell (Figure 4). A littoral cell is a coastal segment that contains a complete sedimentation cycle, including sources, transport paths and sinks. The Oceanside Cell extends from the Dana Point headland southerly to La Jolla Submarine Canyon, a distance of approximately 52 miles. Under natural conditions, a littoral cell is supplied with sediment by rivers and streams that empty into the ocean within its limits. The sandy material brought to the coast by fluvial action is then incorporated into the beach sands and transported along the coast by wave action. This longshore transport of sand is ultimately intercepted by a submarine canyon or other sink, where it is diverted offshore and lost to the nearshore environment.

The Oceanside Littoral Cell is supplied with sediment by San Juan Creek in Orange County, the Santa Margarita, San Luis Rey, and San Dieguito Rivers, and the San Onofre, Las Pulgas, Buena Vista, Agua Hedionda, San Marcos, Escondido, and Los Penasquitos Creeks. Presently over 40 percent of these rivers are controlled by dams and flood control facilities; however, more importantly, significant sand mining activities within the upland watershed has severed the majority of this beach building material to the coastline.

2.5 Littoral Sediments

In the historical past, the Solana Beach coastline has, at times, had a sand beach as much as 100 yards wide (USCGS, 1887-88). Average beach width may have been on the order of 100 feet, recognizing that seasonal beach width fluctuations may also be on the order of 100 feet (Everts, 1991). Although the source of sand from the upland watershed is episodic, only reaching the coastline during significant flood events within the geologic past, sand from the upland watershed has continued to supply the littoral system with an annualized sediment discharge volume estimated by various researchers to vary from 53,000 to 426,000 cubic yards per year, assuming similar climatic conditions (USCOE, 1991). Best-guess estimates for fluvial sediment production range from 160,000 to 200,000 cubic yards per year. The sediment contribution from coastal bluffs is more difficult to evaluate, with coastal erosion contributions estimated to range from 10 percent to 100 percent of the upland fluvial contributions.

Robinson & Associates, under contract to the U S Army Corps of Engineers (USCOE, 1988), estimated the total volume of beach sediments contributed from coastal bluff erosion from 1889 through 1969 to total 28 million cubic yards for the Oceanside Littoral Cell, averaging 351,000 cubic yards per year or approximately 100+ percent of the pre-anthropic inland fluvial contribution. All things considered, this study appears to be flawed, recognizing that along the entire 52-mile stretch of the Oceanside Littoral Cell, approximately 0.7 foot per year of coastal bluff erosion would be required to generate this volume of sediment on an annual basis. This suggests that in the last 80 years, over 50 feet of coastal bluff erosion should have occurred along the entire Oceanside Littoral Cell. On the contrary, at least within the study area, little if any measurable coastal bluff erosion occurred within the first 70 years of this century (Shepard and Grant, 1947; USCOE, 1960; Everts, 1991; USCOE, 1991). Considerable beach nourishment has also occurred on numerous occasions within the Oceanside Littoral Cell since the early 1930s, totaling approximately 10.1 million cubic yards, with 15.6 million cubic yards of sand bypassed around structures within this littoral cell (USCOE, 1991).

The littoral sediments within the Oceanside Cell have primarily originated from the upland watershed, extending easterly some 60 miles to the watershed divide of the peninsular ranges. The watershed drains across Cretaceous and pre-Cretaceous rocks, consisting predominantly of granodiorites, diorites, gabbros, and other coarse-grained plutonic rocks. The river sands which derive from these granitic rocks typically consist of high quality, medium-grained sand, with a D50 grain size on the order of 0.4 mm (excluding the gravel fraction). Table 1 summarizes the results of grain size analyses for various natural and imported sand beaches throughout San Diego County, along with that of Fletcher Cove (Woodward-Clyde Consultants, 1998).

An extensive shingle (gravel) beach also exists throughout much of the study area and throughout most of the Oceanside Littoral Cell. This shingle, which became exposed during storms in 1980 and again in 1983 (Kuhn and Shepard, 1984), originate from the upland watersheds of North County, where the Eocene-aged cobble conglomerates locally exist with maximum thicknesses upwards of 500 feet (Kennedy and Peterson, 1975). Where the conglomeratic formations are incised by rivers, such as San Marcos Creek (Batiquitos Lagoon), the eroded sediments (gravels, sands, silts and clays) are transported to the coast and deposited in nearshore deltas to feed the littoral system. The finer fraction is lost first, and the sands begin their longshore migration until intercepted by a submarine canyon or deposited offshore in water depths too great to enable later onshore movement. The gravels and cobbles, being larger and, hence, less susceptible to both longshore and seasonal offshore-onshore movement, tend to accumulate on the shore platform, or on deeper scoured sand surfaces (as in the case of river mouths) and are re-exposed during periods of sand depletion.

Insufficient information is presently available to definitively explain the seasonal migration of the shingle beach; however, unlike beach sands, the shingle remains relatively stationary and maintains a relatively steep shingle berm fronting the base of the cliffs. The persistence of the shingle beach within the northerly part of the Encinitas coastline has been evident since the early 1980s, and has been noted in Solana Beach for the last few years.

2.6 Bathymetry

Nearshore bathymetry published by NOAA (1980) and Continental Data Systems (1971) suggests a relatively uniform offshore bathymetry out to the 10-fathom contour, with the single exception of the surf break at Tabletop Reef. Average offshore slopes are on the order of 60:1 to 70:1. The Corps of Engineers (Los Angeles District) has profiled one survey range within Solana Beach just north of Fletcher Cove (Range SD600) on an intermittent basis. This range was also reportedly surveyed by the U.S. Coast and Geodetic Survey in April 1894, with essentially no variation in the profile in 60 years (USCOE, 1960). SD600 has most recently been surveyed by the Corps as part of a sand thickness survey report (USCOE, 1988), with the results reported on Figure 5. The results of the 1957 Corps survey have been superimposed upon the 1988 Corps survey; however, it should be noted that we have assumed a backshore width of 100 feet, recognizing that this value was not reported in the 1960 Corps survey. It should be noted, however, that within the 1960 Corps study, backshores were often noted throughout much of the North County coastline. The sand thickness reported in the 1988 Corps study was determined by a jet probe, with the acknowledgment that the onshore measured sand thickness may not accurately reflect the total thickness above the shore platform, acknowledging the presence of an extensive shingle beach below the active sand beach.

Group Delta Consultants (GDC) also surveyed one profile to a depth of 40 feet, extending offshore from 367 Pacific Avenue, with both horizontal and vertical control provided by a Total Station Survey instrument (the same technique as used in the 1988 Corps study). The GDC profile is also shown on Figure 5, and as with the 1988 Corps study, a shingle beach was encountered that we could not penetrate, along with an offshore bar, the approximate extent of which is shown on Figure 5. Both onshore and offshore sand measurements in the GDC study utilized a steel probe, with the tactile feel of the underlying shore platform clearly discernible from the overlying transient sand surface and the underlying shingle beach.

We have also reproduced on Figure 6 a typical offshore profile off of La Jolla, reported by Inman and Bagnold in 1963, illustrating the seaward sloping shore platform in this area, overlain by upwards of 10 feet of sand, having a fairly wide summer backshore. As indicated in the Corps sand thickness survey report (USCOE, 1988), variable-thickness offshore sand deposits exist, extending well beyond the depths of their survey out to the -30 foot contour.

3 EXISTING COASTAL PROCESS ENVIRONMENT

3.1 Wave Climate

The wave climate controls coastal erosion and considerable hindcast data is available to assess future conditions. Accordingly, it is feasible to establish geotechnical and structural design criteria for coastal structures based on the wave climate and, hence, future erosion that may affect a structure during its useful design life.

Waves along the San Diego County shoreline generally range in height from 2 to 5 feet; however, large waves ranging from 6 to 10 feet in height are not uncommon. These large waves, which can arrive at almost any time during the year and may continue for 3 to 4 days, are frequently unaccompanied by strong winds. Breakers with estimated heights of 15 to 20 feet have been observed off the coastline within the study area (USCOE, 1960; National Marine Consultants, Inc., 1960; USCOE, 1991). The recommended 100-year shallow-water design wave for the study area is 19.4 feet (USCOE, 1991).

This section of coastline is exposed to wave action, undiminished by island interference, through only two relatively narrow corridors of wave approach. Waves with periods longer than 10 seconds approach the shore from the northwest between Santa Rosa Island and San Nicolas Island, and from the southwest between Cortez Bank and Los Coronados Islands. The longer-period waves approaching from other directions are obstructed by the various channel islands, Tanner Bank and Cortez Bank, and the Los Coronados Islands.

Short-period waves, with periods of 8 seconds or shorter, generated from the nearshore waters within the various channel islands and offshore banks, have a fetch of 50 to 100 nautical miles and approach the study area from the northwest through the southwest.

Ocean waves off the coast of southern California fall into three main categories:

1. "Northern hemisphere swell," consisting of waves generated in the North Pacific and Gulf of Alaska;

2. "Southern hemisphere swell," consisting of similar waves generated south of the equator; and

3. "Sea," consisting of waves generated within the local area (Munk and Traylor, 1947).

3.1.1 Northern Hemisphere Swell

Winds that produce northern hemisphere swell are usually associated with one of the following meteorological situations (Marine Advisors, 1961):

1. Japanese-Aleutian storms, which move from west to east in relatively high latitudes, often stagnating in the Gulf of Alaska. Occasionally, especially during winter and spring, this storm track shifts southward and the maximum wave heights occur at central or southern California latitudes. These extratropical cyclones are the most important source of severe waves reaching the California coast. The 1982-1983 winter storm season resulted from a series of high-latitude storms, which produced severe conditions responsible for wide-spread destruction along the coast of southern California;

2. Hawaiian storms, which move from west to east in mid-latitudes; or

3. Tropical hurricanes, which commonly develop off the west coast of Mexico. The resulting swell rarely exceeds 2 m (6.5 feet), but a strong

tropical storm will occasionally move far enough north to cause destructive high waves. The storm of September 1939, which passed directly over southern California causing very high waves, is an example (Horrer, 1960).

3.1.2 Southern Hemisphere Swell

Munk, et al., (1963) point out three major source areas: The Ross Sea, the New Zealand-Australia-Antarctic sector, and the Indian Ocean. These southern ocean source areas are partially blocked by island chains in the South Pacific Ocean. The South Pacific is such a large area that waves from several southern storms commonly reach southern California simultaneously. Southern swell is most important during the southern winter from April through September.

3.1.3 Sea

Sea is the term applied to short, steep waves that are still in or near the area in which they are generated. Wind conditions that generate sea vary greatly as one moves offshore from the southern California coast, changing from relatively mild winds over the inner channels, to strong, gusty winds outside the islands.

3.1.4 Summaries of Wave Data

Directional wave information is available from various sources. Among others, Seymour, et al. (1984) have produced storm wave hindcast estimates for the period 1900-1984 using a hindcast location near 35^{E}N, north of Point Conception and the Channel Islands. Only waves with deep-water-approach directions between SOUTHWEST and WNW were considered, because waves approaching more obliquely would be considerably diminished by refraction as they approached the shoreline. Further, the waves were ranked by their power (energy multiplied by period). This resulted in a list of 59 storms in which the resulting offshore significant wave height exceeded 3 m (10 feet), all having periods equal to or exceeding 12 seconds. The tropical cyclone of September 1939, a major wave event in southern California, was added, for a total of 60 storms. These storms are listed in Table 2.

It is of interest to note that extreme deep-water wave episodes exceeding 6 meters were only reported on eight occasions during the period 1900 to 1979, while the period from February 1980 through February 1984 experienced a total of ten storm events with deep-water waves exceeding 6 meters. Further, the storm of January 17-18, 1988, produced the highest measured deep-water waves approaching the southern California coast. The significant wave height was 10.0 meters (Seymour, 1989), higher than any reported in the 1900-1984 database. This storm was likely on the order of a 200-year storm, and was reported by Seymour to be ". . . remarkably similar to Richard Henry Dana's observations in Two Years Before the Mast of the dangerous Southeasters [significant storm arriving from the south] off this same coast during the 1830's."

A statistical evaluation of extreme wave data is also available from various sources, including Marine Advisors (1960), Meteorology International, Inc. (1977), Pacific Weather Analysis (1983, 1987), Fleet Numerical Oceanography Center (1987), Waterways Experiment Station (1987), and Scripps Institution of Oceanography (USCOE , 1989). Scripps Institution of Oceanography (SIO) maintains and operates a network of wave gauges and buoys installed by the Corps of Engineers and the State of California Department of Boating and Waterways, with their data set commencing in early 1975. The SIO wave data measures, wave height, period and direction, and were used to develop a statistical analysis for estimating the 5-, 10-, 25-, 50-, and 100-year reoccurrence interval wave heights for a variety of stations including Del Mar (the closest station to the study area). The following table lists the significant wave height for the various frequency extreme storm events at Del Mar, located in 35 feet of water (USCOE, 1991).

Return Period Years	Significant Wave Height (ft)
5	13.0
10	14.5
25	16.5
50	18.0
100	19.4

3.2 Short-Term Sea-Level Change

The effect of waves on the coast is highly dependent on the sea level during the wave episode. Large waves at low sea level cause limited erosion, since they break well offshore. When episodes of large waves combine with short-term high sea level from tides and other factors, rapid retreat may occur along vulnerable coastlines.

3.2.1 Tides

Tides are caused by the gravitational pull of astronomical bodies; primarily the moon, sun, and planets. Tides along the San Diego coast have a semi-diurnal inequality. On an annual average basis, the lowest tide is about -1.6 feet (MLLW datum) and the highest tide is about 7.1 feet, MLLW datum.

The National Oceanic and Atmospheric Administration (NOAA) collected 18 years of measurements at La Jolla in establishing tidal datums of the 1960 to 1978 tidal epoch (NOAA, 1978). Tidal characteristics at the La Jolla Tidal Station are shown in the following table. The highest recorded sea level at the La Jolla Pier Gauge was 7.81 feet, MLLW, on August 8, 1993.

San Diego Tidal Characteristics at La Jolla
(elevation in feet referenced to mean lower low water, MLLW)

Highest observed water level (Aug. 8, 1983)	7.81
Mean Higher High Water (MHHW)	5.37
Mean High Water (MHW)	1.32
Mean Sea Level (MSL)	2.75
Mean Tide Level (MTL)	2.77
National Geodetic Datum - 1929 (NGVD)	2.56
Mean Low Water (MLW)	0.93
Mean Lower Low Water (MLLW)	0.00
Lowest observed water level (Dec. 17, 1933)	-2.6

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3.2.2 Storm Surge

Storm surge represents the increase in sea level above the astronomical tides due to the combination of low barometric pressure and strong storms pushing sea water against the coast. Storm surge is relatively small along the southern California coast when compared with tidal fluctuations. Excluding the effects of waves, storm surges in southern California rarely exceed 3 feet in amplitude, with average heights below 1 foot for two to six days (USCOE, 1991). Extreme storm surges are presented as a function of return period at selected California tide stations (NOAA, 1980), with those for La Jolla shown below:

Return Period Years	Storm Surge Feet
5	2.0
10	2.1
25	2.2
50	2.3
100	2.4

When storm surge occurs at the same time as a tidal maximum, the combination results in statistical extreme water elevations, with those for La Jolla as follows (NOAA, 1980):

Return Period Years	Extreme Water Elevation Feet (MLLW Datum)
5	7.3
10	7.4
25	7.5
50	7.6
100	7.7

3.2.3 Wave Setup

Wave setup results from superelevation of the water surface over the normal surge elevation due to onshore mass transport of the water by wave action alone. Wave setup is a function of both the stillwater level, and the elevation and slope of the shore platform. For the San Diego area, the typical maximum range in wave setup would likely vary from ½ to 1 foot, which would be added to the extreme water elevation resulting from storm surge and astronomical tide.

3.2.4 El Niño

Large-scale, Pacific Ocean-wide warming periods occur episodically and are related to the El Niño phenomenon. These meteorological anomalies are characterized by low atmospheric pressures and persistent onshore winds. During these events, average sea levels in southern California can rise up to 0.5 foot above normal. Tidal data indicates that six episodes (1914, 1930 through 1931, 1941, 1957 through 1959, and 1982 through 1983, and 1997 through 1998 - mild El Niño-type conditions were also reported in 1988 and 1992) have occurred since 1905. Further analysis suggests that these events have an average return period of 14 years, with 0.2-foot tidal departures lasting for two to three years.

The added probability of experiencing more severe winter storms during El Niño periods increases the likelihood of coincident storm waves and higher storm surge. The record water level of 8.35 feet, MLLW, observed in San Diego Bay in January 1983, includes an estimated 0.8 foot of surge and seasonal level rise (Flick and Cayan, 1984), which set the stage for the wave-induced flooding and erosion that marked that winter season.

3.2.5 Design Stillwater

For design of coastal structures, a conservative high sea level is determined that accounts for all of the factors that may increase sea level during the design life of the structure. This should include tides, storm surge, wave setup, and the increase in sea level that may occur during the design life of the structure. For the Solana

Beach area, assuming a design long-term sea level rise of 1.0 foot, the likely maximum design stillwater elevation would be 7.5 feet (MSL).

3.3 Long-Term Sea Level Rise

Changes in sea level result in significant changes in the shoreline location. Three general sea level conditions are recognized: rising, falling, and stationary. The rising and falling stages result in massive sediment release and transport, while the stationary stage allows time for adjustment and reorganization towards equilibrium. Major changes in sea level during the Quaternary period were caused by worldwide climate fluctuation, resulting in at least 17 glacial and interglacial stages in the last 800,000 years and many before then (Shackleton and Opdyke, 1976). Worldwide sea level rise associated with the melting of glaciers is commonly referred to as "glacio-eustatic" or "true" sea level rise. During the past 200,000 years, eustatic sea level has ranged from about 150 meters below the present-day level, to possibly as high as about 10 meters above the present-day level. If all of the ice presently on earth were to melt, sea level would rise about 78 meters (256 feet) above the present level (Barry, 1981).

Sea level changes during the last 18,000 years (Figure 7; USCOE, 1991) have resulted in an approximately 400-foot rise in sea level, when relatively cold global climates of the Wisconsin ice age started to become warmer, melting a substantial portion of the continental ice caps (Curray, 1960; 1961). Sea level curves show a relatively rapid rise of about 1 meter per century, from about 18,000 years before present to about 8,000 years ago, as indicated in Masters and Fleming (1983). About 8,000 years ago, the rate of sea level rise slowed, ultimately to a relatively constant rate of about 10 centimeters per century since about 6,000 years ago (Curray, 1960; 1961; 1965). Most researchers agree that, along the southern California coastline, the sea level approximately 6,000 years ago was 12 to 16 feet below its current elevation (Curray, 1960, 1965; Inman and Veeh, 1966). More importantly, the world's coastlines, including that of California, have been shaped largely within this 6,000-year period, with the sea at, or within 16 feet of, its present level (Bird, 1985).

Continuous sea level records exist from a tide gauge in San Diego Bay beginning in 1906, and from a gauge at La Jolla beginning in 1924. Figure 8 shows a plot of yearly mean sea level at La Jolla based on data published by the National Ocean Service (NOS). The straight line represents a least-squares fit of the data and indicates a mean rate of sea level rise of 0.64 feet (19.5 centimeters) per century. The shaded areas above the trend line correspond to above-average sea level episodes corresponding to major El Niño events (Quinn, et al., 1978). The highest sea levels in La Jolla were observed on January 29, 1983 (7.71 feet MLLW), and August 8, 1983 (7.81 feet MLLW). These episodes were part of a run of El Niño and storm-influenced extreme events that occurred during the 1982-1983 storm season. [The 8.35-foot extreme tidal level recorded in San Diego Bay during this same period is due to the tidal amplification that occurs within the sheltered bay location.]

Considerable effort has gone into estimating future sea level rise, as this has a significant impact on coastal erosion. The Marine Board Committee on Engineering Implications of Changes in Relative Mean Sea Level, under the direction of the National Research Council, has conducted extensive studies evaluating future changes in sea level (Marine Board, 1987). Representatives of Scripps Institute of Oceanography in La Jolla also participated on the Marine Board . The Marine Board's best estimate for local relative sea level changes affecting San Diego was 16 centimeters per century, taking into account crustal subsidence/uplift. The Marine Board further concluded that tide gauge records contained substantial long-period fluctuations (5-100 years), which indicate that accurate extrapolation of small sea level rise values from the data is very difficult. Determining changes in rates of rise is even more difficult. Figure 9 has been reproduced from the Marine Board study, depicting sea level elevations versus time for relatively stable crustal areas. One should not lose sight of the fact that, excluding the relatively recent sea level records that have been measured for at most the last 90 years, the majority of future sea level predictions are predicated on relatively coarse sea level data extending back for thousands of years before the present.

The reality is that estimated future sea level rise is critically important to estimating future shoreline erosion, as sea level rise drives coastal erosion. Given a known rate of sea level rise, in its simplest form, the amount of erosion in a given time is equal to the amount of sea level rise divided by the shore platform slope. This sea level model takes the following form (Marine Board, 1987):

$$dx/dt = (L + E) / \text{platform gradient}$$

where dx/dt is the horizontal rate of erosion, L is the local tectonic rate of subsidence or uplift, and E is the eustatic sea level rise. With an average platform gradient of 60:1 and a future sea level rise of 16 cm per century, sea level rise alone would result in a retreat of the coastal bluff of approximately 30 feet in the next century. When using the La Jolla sea level rise data of 0.64 feet per century, the sea level rise model would suggest approximately 40 feet of coastal bluff erosion in the next century.

The sea level erosion model described in the previous paragraph has been simplified for clarity and is only accurate when using geologic time scales. Coastal erosion only occurs during periods of direct wave impact, as described in more detail in the following section. Under normal conditions, the protective sand beach provides the primary barrier to direct wave impact, and during large storms, the beach berm is eroded and deposited in an offshore bar, causing the successive storm waves to break on the bar, dissipating most of their destructive wave energy prior to reaching the coastal bluff. As a practical matter, studies of shoreline retreat have really focused on erosion of the sandy beach profile and most of these studies have focused on the concept of an equilibrium beach profile (Fenneman, 1902; Bruun, 1954, 1962; Hands, 1976, 1981, 1983; and others). This is understandable, recognizing that along the east coast and gulf states, erosion-resistant materials equivalent to a shore platform are often tens to hundreds of feet below the active beach profile. Although a variety of relationships have been developed to quantify the equilibrium profile, on the geologic time scale, the preceding sea level model equation accurately describes the rate of coastal erosion, recognizing that the erosion itself occurs in a series of discrete steps.

Along the west coast, where virtually the entire coastline from the tip of Baja to the Canadian border, consists of coastal bluffs, very unlike the eastern seaboard, and resulting from differing plate tectonics, i.e., a leading edge coast versus a trailing edge coast, the entire offshore profile, extending out to the continental shelf, consists of an erosion-resistant bedrock abrasion surface intermittently capped by relatively recent (within the last

18,000 years) beach sands that have been pulled offshore primarily during storms and lost to the littoral system, remaining in place as sea level continues to rise.

This is an important concept in that the available data suggests that, prior to the late 1970s, the last period of significant coastal retreat occurred in the late 1800s (1860s - 1890s), when the combined sediments from the upland watershed and erosion of the coastal bluffs provided a stable, albeit dynamic, equilibrium profile, with the entire nearshore shore platform, extending beyond the littoral zone, fully charged with sediment due in part to significant offshore losses from the littoral zone from the many storms during the later part of the last century (Kuhn and Shepard, 1984; May, 1987). With a healthy beach berm, the more infrequent storms that occurred during the first part of the 20th century would temporarily displace sand offshore to form the winter profile with the protective offshore bars, with a net loss of the protective sand beach essentially following that of the Marine Board sea level model.

The progressive and rather significant loss of upland sand sources within the Oceanside Littoral Cell over the last 60 years, coupled with the offshore displacement of littoral sediments deflected out of the littoral system by the Oceanside Harbor breakwater[1], have resulted in a significant and almost total loss of the protective transient sand beach and, hence, future erosion rates should now more systematically follow the sea level erosion model, only amplified somewhat due to the loss of the historical (pre-anthropic) protective sand beach.

Referring back to the Marine Board study, the very real potential exists for the La Jolla data to suggest the beginnings of a more rapid sea level rise. The Marine Board was also tasked with developing a variety of sea level rise scenarios addressing global warming, with the most conservative scenario predicting 1.5 meters (4.92 feet) of sea level rise by the year 2100 (Marine Board, 1987). This rather dire prediction would translate into an average beach erosion rate of almost 3 feet per year, or approximately 295 feet of shoreline retreat in the next century.

[1]The USCOE (1987, 1991) Oceanside Littoral Cell Preliminary Sediment Budget Report concluded that southerly littoral transport upon reaching the Oceanside Harbor breakwater is deflected offshore via a strong rip current depositing the majority of the littoral sediment outside of the littoral zone.

4 MECHANICS OF CLIFF EROSION

The Solana Beach coastline has experienced a measurable amount of erosion in the last 20 years, with the most significant amount of erosion occurring during this past winter's El Niño storm season. The entire base of the seacliff is currently exposed to direct wave attack all along the coast. The waves erode the seacliff by mechanical abrasion at the base of the seacliff, and by impact on small joints and fissures in the otherwise massive rock units, and by water-hammer effects. The upper bluffs, which typically support little or no vegetation, are subject to wave spray and splash, sometimes causing saturation of the outer layer and subsequent sloughing of oversteepened slopes. Wind, rain, irrigation and uncontrolled surface runoff contribute to minor erosion of the upper coastal bluff, especially on the more exposed, oversteepened portions of the friable sands. Where these processes are active, rilling has resulted along portions of the upper bluffs.

Bluff-top retreat under natural conditions is the end result of erosion processes (both marine and subaerial) acting primarily on the seacliff and upper bluff. The contribution from erosion of the coastal terrace (landward of the bluff top) is generally smaller and can be reduced to negligible amounts by careful landscaping, control of surface runoff, and prevention of human traffic near the bluff top.

Geomorphic techniques can be used to describe the progressive nature of bluff-top retreat. This requires breaking the problem down into upper and lower bluff (seacliff) component processes, and developing an understanding of the interaction between the two components.

Although bluff retreat is episodic and site-specific, characteristically coinciding with major storm events, the rates of retreat of both upper and lower components of the bluffs at Solana Beach are approximately equal over the longer term (defined here as several hundreds of years). Continuing long-term retreat of the lower bluff gradually creates an oversteepened slope in the upper bluff, causing it to decline (by erosion and/or slope failure) to a more sustainable angle of repose. The process continues and repeats in a series of episodes. In the Solana Beach area before the 1997-98 El Niño storm season, upper-bluff slope inclinations characteristically ranged between approximately 37 and 53 degrees. As the upper bluff slope approaches the high end of this range, episodes of massive slope failure are typically caused by insufficient soil strengths to sustain the steeper slope angles and are often aggravated by the combined effects of groundwater seepage and rainfall.

4.1 Marine Erosion Processes

The types and rate of marine erosion affecting the typical Solana Beach bluff profile will change with the tidal level and shore platform elevation. Marine erosion is caused by mechanical and biological processes that backwear the sea cliff and downwear the shore platform. In addition, variations in seafloor bathymetry may result in wave focusing, further exacerbating erosive wave forces.

4.1.1 Mechanical and Biological Processes

Mechanical erosion processes at the cliff-platform junction include water abrasion, rock abrasion, cavitation, water hammer, air compression in joints, breaking-wave shock and alternation of hydrostatic pressure with the waves and tides. All of these processes are active in backwearing. Downwearing processes include all but breaking-wave shock (Trenhaile, 1987). Backwearing and downwearing by the mechanical processes described above are both augmented by bioerosion, the removal of rock by the direct action of organisms (Warme and Marshall, 1969; Trenhaile, 1987). Backwearing and downwearing typically progress at rates that will maintain the existing gradient of the shore platform. In the Solana Beach area, the rate of downwearing is approximately one to two percent of the rate of backwearing, based on slope of the shore platform.

Transient shingle beaches, composed primarily of rounded cobbles and gravel, exist along portions of the coastline. These deposits, when present in limited quantities, tend to accelerate mechanical abrasion causing the formation of a notch at the base of the cliff-platform junction, eventually destabilizing the vertical overhang causing its collapse and accelerating marine erosion. Shingle beaches comprised of a significant amount of cobbles and gravels will reduce the impact of wave energy at the base of the seacliff during normal sea and moderate storm conditions; however, it has been shown that during times of extreme storms accompanied by high energy wave conditions, both the shore platform and seacliff may still experience higher levels of measurable erosion as a result of cobble abrasion and the impact of clasts acting as projectiles (Kuhn and Shepard, 1984; 1985).

The Torrey Sandstone appears to be one of the least resistant bedrock units exposed in the North County coastal bluffs. Where exposed to marine erosion, a significant amount of notching occurs at the base of the bluff in the Torrey. The erosion susceptibility of the various lower geologic units is both a function of the rock lithology and structural discontinuities within the rock. The Torrey Sandstone has unconfined compressive strengths on the order of 80 to 100 pounds per square inch, where the other Eocene-age units exposed in the North County coastal bluffs have unconfined compressive strengths ranging from 100 to 150 pounds per square inch. In general, the lithology of the cliff-forming Eocene-age geologic formations throughout the Solana Beach coastline is similar enough to suggest fairly uniform susceptibility to abrasion and other forms of marine-induced erosion.

Photo No. 12 (Folger collection) shows the late January 1998 collapse of a significant section of coastline below 371 to 403 Pacific Avenue, resulting from the notching that eventually undermined a linear section of the bluff beyond bluff-parallel jointing, triggering a slab-type failure to occur. Note the presence of the sea caves, which are unassociated with the slab-type failure.

4.1.2 Water Depth, Wave Height, and Platform Slope

The key factors affecting the marine erosion component of bluff-top retreat are water depth at the base of the cliff, breaking wave height, and the slope of the shore platform. Due to the almost total absence of a protective sand beach and a shore platform elevation at the base of the seacliff near elevation -1 foot, MSL, for the majority of any given day, waves are impacting directly upon, and actively eroding, the coastal bluff.

Along almost the entire coastline, the seacliff is subject to attack by breaking and broken waves, which create the dynamic effects of turbulent water and the compression of entrapped air pockets. When acting upon jointed and fractured rock, the "water-hammer" effect tends to cause hydraulic fracturing which exacerbates seacliff erosion. Erosion associated with breaking waves is most active when water depths at the cliff-platform junction (d_s) coincide with the respective critical incoming wave height (H) such that d_s is approximately equal to 1.3H.

Waves will break when their height reaches approximately 75 percent of the water depth; thus, assuming a denuded sand profile with the shore platform elevation at the base of the seacliff at elevation -1 foot (MSL), 3-foot-high waves would break at the base of the seacliff when the stillwater level (SWL) is approximately 3 feet above mean sea level (5.75 feet MLLW), corresponding to 4 feet of water depth at the base of the sea cliff.

When the shore platform is protected by a sand or shingle beach, breakers would form some distance offshore from the bluff. These waves would shoal, break, reform as smaller waves or proceed shoreward as broken waves, ultimately delivering to the seacliff only a small fraction of the original wave energy.

4.2 Subaerial Erosion Processes

The process of upper bluff slope decline is illustrated in Figure 10 (Leighton, 1979). This Figure illustrates the impact of marine erosion on subaerial erosion, and the process by which marine erosion of the seacliff continually acts to steepen the relatively gently-sloping upper bluff surface from the bottom-up of a Type "C(c)" coastal bluff, which does not have a cemented cap.

Considerable investigative work has been conducted on the process and mechanisms of slope decline in an attempt to date fault scarps, which are subsequently affected by subaerial erosion. Wallace (1977) developed slope decline criteria for weakly indurated Pleistocene deposits similar to that of the on-site marine terrace sands (Figure 11). As depicted, the initial steeper section of the curve represents more rapid decline from about 10 to 100 years of age, primarily associated with progressive surficial slumping, typical of that shown on Figure 10. Below an inclination of about 35 degrees, coincident with a 100-year age date, decline continues at a much slower rate, primarily associated with rilling, rain impact, raveling, and in-place weathering.

As part of a coastal bluff study conducted for Encinitas, Dr. Shlemon, a noted Quaternary Geologist, was able to determine paleosol development, suggesting in-place weathering void of any coastal bluff erosion for a period of approximately 75 to 100 years within the northernmost section of Encinitas. In this area, relatively stable upper-bluff slopes of 35 to 40 degrees, consistent with those described by Wallace (1977), suggested essentially no subaerial erosion dating back to the 1890s, and thus suggesting no substantive marine erosion during this same time period (Group Delta Consultants, 1993). Upper-bluff slopes within the study area of Solana Beach, where unaffected by recent slope failures, are slightly steeper and do not appear to have developed a paleosol. However, when comparing the geomorphic conditions affecting the two sites, combined with the relatively extensive cemented beach ridge deposits in the study area, we are of the opinion that slope retreat in the more stable areas dating back to the early 1900s is likely limited to a few feet.

Coastal bluffs that have a resistant cap of partially-cemented sand or other soil are more resistant to slope decline and behave more like the type "B(c)" bluff in the Emery and Kuhn (1982) classification (Figure 3). The cap appears to protect the underlying upper bluff from attack by rain and runoff, which weakens the intergranular structure of unprotected sediment. The rate of erosion of the partially cemented cap is much slower than the rate of unprotected sediment and strongly influences the rate of bluff retreat. The cap is subject to undermining by progressive slumping and erosion working its way upward from the sea cliff. The Wallace curve likely underestimates the contribution of the erosion resistant cap, and where this exists, coastal bluffs can sustain higher slope angles than predicted by the Wallace curve [the slopes in Encinitas where Dr. Shlemon found well-developed paleosol horizons, did not have the cemented cap typical of the Solana Beach coastline].

Groundwater seepage exiting the bluff face on top of the Eocene bedrock units tends to cause spring sapping and solution cavities along faults, joints and bedding planes, locally accelerating marine erosion, and contributing to subaerial erosion, in these areas. Additionally, as groundwater approaches the bluff, it infiltrates near-surface, stress-relief, bluff-parallel joints, which form naturally behind and parallel to the bluff face. Hydrostatic loading of bluff-parallel (and sub-parallel) joints contributes to block-toppling failures in the lower cliffed sections of the bluff.

Although groundwater seepage may locally exist throughout the study area, groundwater seepage exiting the bluff face was only noted at the back of the sea cave below 205 Pacific Avenue and in the vicinity of Fletcher Cove at the contact between the upper terrace deposits and the underlying Pleistocene-age canyon infill.

5 ANALYTICAL METHODS

In its broadest sense, geomorphology deals with land forms and their evolution over time. Lithology, or the description of the physical character of rocks, can also be used to estimate the relative erosion resistance of the intact, non-fractured rock. Geologic structure, which includes structural discontinuities such as jointing and faults, can be used to estimate variations in erosion resistance within a particular lithologic unit. Coastal processes include waves impacting upon coastal bluffs. This is the basic source of erosive energy, which is modified by the nearshore and offshore bathymetry, and by sea level elevation relative to the nearshore bathymetry. More recently, natural coastal geomorphic processes have been influenced by anthropic activities.

The methodologies most useful to assess relative rates of coastal erosion are divided into five general separate categories:

1. Historical analyses;
2. Geomorphic analyses;
3. Anthropic influences;
4. Impact of long-term sea level change; and
5. Empirical and analytical techniques.

Coastal geologists and geomorphologists traditionally employ the first three techniques, often relying on interpretation of maps and aerial photographs. However, such historical data usually cover a short time span and may be limited to small-scale maps and photographs such that significant errors may occur in estimating the amount and rate of shoreline change. If the available maps and photographs cover only a quiescent climatic period, underestimates are likely. The details of each methodology are discussed in the following paragraphs.

5.1 Historical Analyses

Historical data often include maps, charts, photographs, survey notes, reports, newspaper clippings and eyewitness accounts (Fulton, 1981). Useful historical information about coastline changes in San Diego County extends back to the later part of the 19th Century, and reasonably accurate climatological data dates back to the early 1800s. Stereoscopically-paired vertical aerial photographs (typically at a scale of 1:24,000) are available from 1928, and good-quality, low-angle oblique photographs (at a scale of 1:2400) date back to 1954. Ground-level, close-up photographs, which are usually the most useful to assess site-specific changes in the coastline, are not abundant, but locally are available from the personal collections of private individuals and from historical societies and museums. Successive ground or aerial photographs, dated drawings, or even paintings that show former coastal configurations, are very useful to assess short-term (historical) rates of erosion (Bird, 1985).

Summary conclusions from the 1960 USCOE report on "Beach Erosion Control, Cooperative Study of San Diego County, California," prove insightful regarding early survey work in the site vicinity.

> *Batiquitos Lagoon to Soledad Way - Examination of the surveys indicates that the mean high water shoreline from Batiquitos Lagoon to Soledad Valley was essentially unchanged between 1887 and 1934. The 1957 mean high water line is slightly seaward of the 1934 line at Moonlight Beach in Encinitas. At the mouth of the San Dieguito River near Del Mar, the 1957 mean high water line is unchanged from the 1934 location. It is believed that no serious bluff erosion occurred along this section of the coast between 1887 and 1934.*
>
> *The mean lower low waterline of 1934 is about 100 feet shoreward of the 1887 line along this entire length of shore from Batiquitos Lagoon to Soledad Valley and the 1957 mean lower low waterline, in general, follows the 1934 line. The 1887 and 1934 surveys were examined and no difference could be found in the location of the bluff lines as no serious bluff erosion occurred along this section of coast between 1887 and 1934. The high bluffs, which back the narrow beach*

through the communities of Encinitas and Leucadia, are undercut at an elevation of about +15 feet, but this appears to be the result of the cutting action of windblown sand rather than wave erosion.

The San Diego County coastline has been portrayed in various maps and charts dating back to the 1800s. A prime source of coastal maps is the National Oceanic and Atmospheric Administration (NOAA), which in cooperation with the Los Angeles District (COE) has produced shoreline-movement maps at a scale of 1:24,000 extending from Portuguese Point (Long Beach) on the north to the Mexican Border on the south (USCOE, 1985, 1987). The maps compile coastline data, in part from the U.S. Coast and Geodetic Survey, extending back to 1887 along the coast, and back to the 1850s in the bays, and show gross changes in the shoreline. However, at this scale, erosion amounts of less than 50" feet are not distinguishable.

Considerable work has also been done to evaluate the accuracy of comparing historic and contemporary small-scale mapping (Crowell and others, 1991). In Crowell's study, maps with scales as large as 1:10,000 were considered. A computed erosion rate is based on an apparent map difference (subject to mapping resolution inaccuracies) divided by the time span between maps. A very old map of lesser accuracy may yield a more accurate erosion-rate estimate than a recent map, because more time allows coastal change to accumulate to detectable amounts. The results of these studies generally indicate that typical resolution of principal identifiable features in mapping performed prior to 1930 may have a horizontal error of 13 feet, indicating that erosion rates estimated by comparison to these maps have a resolution of at best two inches per year. Maps produced from 1934 to 1938, using early photogrammetric methods, are highly variable in quality, with horizontal error exceeding 36 feet in some cases, indicating erosion-rate resolutions of at best nine inches per year. Topographic maps produced through the late 1950s, using more contemporary photogrammetric methods, have horizontal error of about eight feet, yielding potential erosion-rate resolutions of at best three inches per year. Since the early 1960s, map quality based on photogrammetric methods has improved to the point where a typical horizontal error would be less than five feet.

Larger-scale topographic maps dating back to the early 1950s are available for most of San Diego County at a scale of 1:2400. These maps were prepared using photogrammetric methods and provide a useful baseline for evaluating coastal erosion during the last 30 to 40 years (County of San Diego, 1960, 1975, 1985).

Even comparison of contemporary maps is subject to error, especially when the maps are produced only a few years apart. In general, successive high-resolution photographs showing readily-identified coastal features provide the best record of progressive shoreline change.

A review of aerial photographs flown since 1928, as well as oblique aerial and land photographs of the Solana Beach coastline area dating back to 1954, indicates a general lack of observable marine erosion prior to the January 1978 storms, with subsequent erosion occurring in discreet events in response to major storms.

Although photographic evidence of marine erosion was apparent as early as 1978, no quantifiable amounts could be discerned from the available aerial photographs. The first obvious recognizable amount of marine erosion occurred during the 1982-83 storm season, where numerous sea caves and notches developed, with upwards of 6 to 8 feet of marine erosion locally scouring into the base of the seacliff, and possibly upwards of 1 to 2 feet of marine erosion occurring along the remaining portions of the Solana Beach coastline.

The 1982-83 storms also completely removed the nearshore beach sands from the shore platform for a period of time, exposing the nearshore shingle deposits and enabling storm waves to break directly on the base of the sea cliff, contributing to both sea cave and notch development.

The 1997-98 El Niño storm season caused extensive additional retreat of the sea cliff throughout most of the study area, where significant sea caves and notches developed and subsequently collapsed, resulting in upwards of 15 feet of sea cliff retreat, significantly undermining the upper sloping terrace deposits and locally developing significant additional caves and notches, some of which have been infilled under recent emergency permits and some remain to this day.

5.2 Geomorphic Analyses

Geomorphic analyses include all factors that contribute to shaping coastal landforms. Coastal erosion and coastal-bluff retreat are caused by both marine and terrestrial processes. Surf action is usually the dominant marine agent producing both hydraulic (wave) impact and abrasion. A basic understanding of the various geomorphic processes is clearly a requisite to assess variations in shoreline erosion. Geomorphic analysis, including coastwide geologic inventory, measurements of offshore bathymetry, and research to determine historic climatic conditions permits assessment of likely future coastal erosion. The relationships between the factors provide the coastal consultant the necessary tools for evaluating future trends in coastal erosion.

Geomorphic factors that contribute to coastal erosion are mainly:

- Climate. Long-term climatic and short-term meteorologic conditions produce large waves, the energy source causing coastal erosion. Storm conditions may present a variety of wave directions, heights, and frequencies.

- Offshore Geology and Wave Energy. The amount of wave energy impacting a seacliff is locally controlled by the offshore seafloor bathymetry of the shore platform, which is influenced by lithology and faulting. The shore platform causes large, deep-water waves to break before reaching the shoreline, thereby attenuating the amount of wave energy ultimately impacting the seacliff. Variations in nearshore bathymetry also refract ocean waves, locally focusing damaging wave energy onto certain coastline segments (Munk and Traylor, 1947; Bradley and Griggs, 1976).

  Clearly, the presence of Tabletop Reef shelters the northernmost portion of the study area and causes refraction of incoming waves that may result in increased erosion elsewhere along the coast.

- Lithology and Structure of Coastal Bluffs. Lithology is the physical character of the rock, which provides the erosion resistance of the rock type.

Structure is the discontinuities in the rock that cause variations in erosion potential for a given rock type. These two factors may vary greatly along a stretch of coast, and are primary factors in site-specific rates of coastal retreat.

- Groundwater. The presence of groundwater may significantly impact the stability of certain geologic units and consequently accelerate bluff retreat. Groundwater seepage also tends to weaken intact geologic units (Kuhn and Shepard, 1980) by both chemical solution and by mechanical erosion, thus increasing susceptibility of soils in the bluff face to accelerated marine erosion, and assisting formation of caves along small faults by wave action in the seacliff (Kuhn and Shepard, 1983).

  The significant topographic relief carrying the surface drainage from the top of the bluff, combined with the permeable nature of the Eocene-age Torrey Sandstone, minimizes the susceptibility to groundwater-induced coastal bluff failures within Solana Beach.

- Bluff Geometry. Bluff geometry is the shape of the coastal-bluff profile. Bluff geometry is influenced by marine erosion from coastal processes at the seacliff, and subaerial erosion from terrestrial processes acting on the bluff (Emery and Kuhn, 1982). The rate of marine erosion at the seacliff limits the decline of the bluff caused by subaerial erosion. Because the upper coastal bluffs along the Solana Beach coastline are all subjected to similar terrestrial processes (excluding man's activity), a qualitative assessment of bluff retreat can be made based on variations in bluff geometry along the coastline.

- Measurement of Slope Retreat. A classic tenet of geomorphology is that slope angles decrease with the passage of time. Measurement of bluff profiles enables an evaluation of the relative amount and rates of marine and subaerial erosion. The rate of slope decline is nonlinear, consisting of an initial rapid decline, followed by progressively slower decline. Regardless of origin -- fault, fluvial, or coastal bluff -- all slope decline follows the same rule. The age of the slope can be estimated from the angle of the slope (Wallace, 1977).

As part of the aging process, the near-surface portion of the bluff develops a weathering profile (pedogenic soil) that may form on at least part of the slope. The relative development of the weathering profile is thus an indicator of slope age. For coastal bluffs, the rate of marine erosion of the seacliff limits the development of a weathered soil horizon on the upper sloping surface.

5.3 Anthropic Influences

Human activity significantly influences shoreline changes, both directly, by erosive activities along the bluff top and seawall building at the base of the bluff, and indirectly, exemplified by the pervasive impact of activities in the upland watersheds, such as periodic burning of surface vegetation by fires, the construction of dams and sand mining.

Until recently, longshore transport annually moved on the order of 200,000 to 300,000 cubic yards of sand through the Oceanside Littoral Cell, which encompasses some 52 miles of coastline terminating at the La Jolla Submarine Canyon (Nordstrom and Inman, 1973; USCOE, 1987, 1991). Under these natural conditions, a relatively persistent sandy beach was maintained since available longshore transport energy was not sufficient to cause a long-term beach deficit. It has been estimated that about 500 to 900 feet of shoreline erosion has occurred in the Solana Beach area in the last 6,000 years. This erosion occurred in the presence of beaches maintained by abundant sediment sources from rivers and the coastal bluffs themselves.

Since the 1940s, approximately 40 percent of this sediment-producing watershed has been dammed (Nordstrom and Inman, 1973; COE, 1987, 1991), and concurrently large volumes of river sands have been mined from the lower reaches of North County rivers for use in the construction industry. This human activity in the last 50 years has resulted in a pervasive long-term sediment deficit (Inman, 1976; USCOE, 1991). The current sediment deficit has essentially denuded the shore platform of sand, resulting in an underwater topographic environment somewhat different than what has typically existed in recent geologic times. The lack of sand has created a more severe coastal environment than would normally exist under natural conditions.

In addition to recreational opportunities, sand beaches provide natural protection against damage from wave action and flooding. The absence of protective sand beaches also allows the direct impact of breaking waves on coastal bluffs and the accelerated erosion of the bluff. The San Diego Association of Governments (SANDAG) has formed a Shoreline Erosion Committee to address coastal erosion in San Diego County, and has concluded that "the shoreline is a valuable asset to the environment and economy of the San Diego region and the state. It is also considered a resource of significant national significance. The beaches and sea cliffs help define this area's quality of life; when we think of the region's positive image, we most often think of the climate and the shoreline." The basic conclusion of SANDAG's Shoreline Preservation Strategy is that a beach building and maintenance program is recommended as the primary shoreline management policy for control of shoreline erosion (SANDAG, 1993).

Throughout the Oceanside Littoral Cell, average beach widths were surveyed, with results reported in the SANDAG study for Solana Beach in 1990 as 80 feet [beach width was defined in the SANDAG study from the MSL contour to the base of the sea cliff]. Future projected average beach widths for the years 2010 and 2040 were 70 feet and 35 feet, respectively [as a point of reference, using the SANDAG definition, the current beach width, measured during our field surveys in mid June 1998, ranged from 0 to 40 feet, with an average width on the order of 20 feet; somewhat less than the year 2040 prediction. Please note also that this beach width definition creates a deceptively wide beach, recognizing that beach widths are typically defined as extending out to MHHW or at times to the landward edge of the foreshore. The former results in an average current beach width of 0 to 10 feet, and the latter results in no beach].

The SANDAG study then evaluated the required minimum beach width to protect the coastal bluff, accommodating both seasonal fluctuations and a 100-year storm event. For the Solana Beach coastline, that width was determined to be 232 feet. The SANDAG study further concluded that the required volume of beach fill within the Oceanside Littoral Cell was 25,000,000 cubic yards, with a future annualized renourishment volume of 320,000 cubic yards per year. One of the recommendations contained in the SANDAG Shoreline

Preservation Strategy was the need to provide additional beach nourishment to accommodate recreational demand, with the year 2040 total demand requiring an average beach width of 325 feet.
Anthropic activities have also locally influenced rates of bluff-top retreat and bluff-slope decline by uncontrolled and concentrated surface drainage, and by surface alterations ranging from early farming to more recent residential bluff-top development (Kuhn and Shepard, 1980; 1985).

In any assessment of future coastal erosion, one must address the impact of human activity, and recognize that the historical database cannot simply be projected into the future without considering human impact.

Human activities in the last 50 years have resulted in the progressive loss of the transient sand beach, primarily from the cumulative effects of sand removal in the urbanizing watershed. This has caused a dramatic increase in the rate of marine erosion not previously observed during man's initial habitation of the North County coastal area.

5.4 Impact of Long-Term Sea-Level Change

An entirely independent method of assessing the rate of coastal erosion is to consider long-term (geologic) sea-level change, which is the major factor determining coastal evolution (Emery and Aubrey, 1991). Sea level rise drives coastal erosion and has been discussed in detail in Section 3.3.

Tectonic activity can also account for significant relative changes in sea level in a local area. Past movement along the Rose Canyon fault zone and associated faults, which uplifted Mount Soledad and formed Point La Jolla, also created a zone of structural weakness along which the La Jolla Submarine Canyon has been incised. The Torrey Pines block, with its relatively horizontally stratified Eocene-age formations and wave-cut terraces, has experienced approximately 500 feet of tectonic uplift in the last 2,000,000 years, while the tilted and uplifted Soledad Mountain block has undergone more than 800 feet of tectonic uplift in the same period (Kern, 1977). The Eocene and Miocene shorelines shown on Figure 12 show the major impact of tectonic sea-level change on shoreline erosion and shoreline location (Howell and others, 1974). Differential tectonic uplift is responsible for the 8-foot variation in the elevation of the Pleistocene-age (12,000 years before present) wave-cut abrasion platform along the 4,000-foot-long study area.

5.5 Empirical and Analytical Techniques

The scientific community has been actively engaged in developing numerical models to assess rates of shoreline erosion. Numerical models attempt to address both the landward retreat of the seacliff, and the development of the shore platform. In this simplest expression, predictive cliff-erosion models take the following form (Sunamura, 1977):

$$dx/dt \propto \ln\left(\frac{f_w}{f_r}\right)$$

where dx/dt is the horizontal rate of erosion, f_w is the wave force, and f_r is the rock resistance. Similar equations have been developed to describe platform development.

Although the rate of erosion is a function of both rock strength and wave force, more importantly, these numerical models describe that, for a given unconfined compressive strength, the rate of erosion is proportional to the natural log of the wave force and, thus, not linearly increasing with increase in wave height. This is important for two reasons. Initially, since breaking waves are depth limited, and more a function of the still water depth at the base of the sea cliff, it is the high tides, coupled with barometric low pressure, storm surge and wave setup, that define maximum still water elevation and, hence, the depth-limiting breaking wave force, i.e., f_w. Additionally, the presence of a protective sand beach, which limits (or eliminates) the still water depth at the base of the bluff quickly reaches a threshold below which no additional marine erosion occurs.

For the past century, the eustatic sea level rise has averaged 0.0052 foot per year (Marine Board, 1987). Thus, using the average shore platform slope [extending out to the -14 foot contour] of 0.0156 (14'/900') results in an average seacliff erosion rate of 0.33 foot per year. Using the La Jolla tidal data, suggesting 0.64 foot per century, results in an average sea cliff erosion rate of 0.41 foot per year.

6 IDENTIFICATION/DESCRIPTION OF REPRESENTATIVE REACHES

For purposes of this evaluation the Solana Beach coast has been divided into seven reaches on the basis of characteristics of the lower seacliff, upper coastal bluff, and offshore bathymetry. Measurements of sea caves, notches and overhangs are summarized on Table 3 and reflect the results of our field surveys completed in June and July 1998. Sea cave and notch depths noted on Table 3 and shown on the topographic base maps reflect conditions in June and July 1998, after the seasonal onshore movement of sand had covered the bottom and rear portions of the abrasion features. Therefore, the depths measured during our field surveys likely underestimate the actual depths of notches and sea caves. The photogrammetrically prepared topographic base map was flown on June 18, 1998, during the tidal low of +0.7 foot, MLLW. The low altitude oblique aerials, Photos 1 through 8, were flown on July 9, 1998, during the tidal low of 2.0" feet, MLLW. The seven reaches are as follows:

Reach	Identification
1	Cardiff State Beach to 533 Pacific Avenue
2	529 to 517 Pacific Avenue
3	Tide Park - 509 to 501 Pacific Avenue
4	475 to 235 Pacific Avenue
5	231 to 139 Pacific Avenue
6	Fletcher Cove
7	Las Brisas

6.1 Reach 1 - Cardiff State Beach to 533 Pacific Avenue

This reach of the coast is characterized by small coves and headlands, a significant offshore reef (Tabletop Reef), which reduces the amount of available wave energy reaching the coastal bluffs, a comparatively wide beach, open sea caves, and the absence of a partially cemented cap of beach ridge deposits. The reach is shown on Map and Photo 1 and 2, and represented by Cross Section 1 at 617 Circle Drive, Figure 13.

At the time of our field surveys, the beach was 50 to 100-feet wide (defined here as above MHHW) and extended up to elevation 8 feet at the base of the sea cliff. Offshore, the bedrock shore platform was exposed. The near-vertical sea cliff rises to elevation 18 feet, followed by the bluff at a typical slope angle of 37" degrees to elevation 63 to 68 feet. Existing sea caves extend 30" feet into the cliff, which consists of Del Mar Formation north of 629 Pacific Avenue and interbedded Del Mar and Torrey Sandstone to the south. The Del Mar Formation introduces clayey layers that are more susceptible to erosion than the enclosing sandstone. The clay layers usually form the roofs and floors of the sea caves, while faults and joints control the sides.

Comparison of the 1990 and 1998 topographic profiles in Cross Section 1 suggests 10" feet of retreat of the sea cliff in the last eight years. Accelerated subaerial erosion affects the lower bluff below 629 and 633 Circle Drive. The two slope failures affecting the top of the bluff at 617 Circle Drive were reportedly caused by excess irrigation saturating the upper marine terrace deposits. The larger, northern slope failure caused loss of approximately 8 feet of the upper bluff and deposited a debris cone on the beach that extends above the bedrock contact. At the north side of the slope failure is an active over-bluff drainage.

A seawall protects the sea cliff at 645 Circle Drive. Recent cliff retreat at the south end has caused exposure of several feet of the south abutment of the wall.

6.2 Reach 2 - 529 to 517 Pacific Avenue

Reach 2 is characterized by small coves and headlands, limited beaches consisting primarily of shingle, limited mitigation of wave energy only from the northwest, numerous sea caves, all of which have been filled, and the northernmost limit of partially cemented beach ridge deposits. The reach is shown in Map and Photo 3, and represented by Cross Section 2 at 529 Pacific Avenue, Figure 14.

The beach varies from 0 to 20 feet in width, extending up to elevation 5 feet at the base of the sea cliff in the coves. Offshore, the shore platform is underlain by exposed bedrock. The near-vertical sea cliff rises to elevation 18 feet, followed by the bluff at a typical slope angle of 41" degrees to elevation 63 to 80 feet. Numerous sea caves extend up to 30" feet into the cliff, which consists of interbedded Del Mar and Torrey Sandstone. The Del Mar Formation introduces clayey layers that a more susceptible to erosion than the enclosing

sandstone. The clay layers usually form the roofs and floors of the sea caves, while faults and joints control the sides.
Comparison of the 1990 and 1998 topographic profiles in Cross Section 2 suggests 4 to 6 feet of retreat of the sea cliff in the last eight years. The top of the bluff has retreated 0 to 4 feet in the last 6 years, based on comparison with February 24, 1992, aerial photographs in our files. Accelerated subaerial erosion affects only a small part of the bluff below 529 Pacific Avenue. An active over-bluff drainage descends from the property line between 529 and 533 Pacific Avenue.

A seawall, riprap, and geogrid slope were constructed at 521 Pacific Avenue to repair collapse of the largest sea cave in North County.

6.3 Reach 3 - Tide Park - 509 to 501 Pacific Avenue

This reach of the coast is a cove and pocket beach protected by headlands. The reach is shown in Map and Photo 3. The back of the cove has been protected by a concrete sandbag seawall that appears to have performed well except where repairs have been required at both ends. The cove is protected by a substantial headland on the north and a thin headland on the south that supported a lifeguard tower up to 1997. At the time of our surveys, the average beach width within the cove was 60 feet.

6.4 Reach 4 - 475 to 235 Pacific Avenue

Reach 4 is characterized by a long straight sea cliff between two headlands. This entire reach experienced extensive block falls during the El Niño of 1997-98. The near-vertical seacliff was severely undermined by notching at the base, leading to overhangs that collapsed in large blocks, carrying parts of the overlying and sloping upper bluffs with them, and leaving unstable, near vertical cliffs in the lower portions of the weak marine terrace deposits. During our field surveys, an active block fall had detached itself from the coastal bluff below 269 Pacific Avenue. The reach is shown on Map and Photo 4, 5, and 6, and represented by Cross Sections 3 through 10, Figures 15 through 22, respectively.

Fresh scars from block falls mark the sea cliff and upper bluff below 20 of the 28 residences in the reach, from 245 to 309 Pacific Avenue, from 327 to 337 Pacific Avenue, 347 to 403 Pacific Avenue and 417 to 423 Pacific Avenue. Areas outside the identified address ranges may have experienced block falls early in the period of wave attack but lack fresh scars because of subsequent marine erosion. Remaining notches range up to 6 feet in depth, but overhangs locally range up to 9 feet. Steep and near-vertical scars extend as high as elevation 60 feet at 371 Pacific Avenue.

The sand beach varies from 0 to 20 feet in width, extending up to elevation 5 feet at the base of the sea cliff in the cove at the north end. Small areas of shingle beach exist along the base of the cliff. Offshore, the shore platform has a thin, discontinuous layer of sand up to 18-inches thick (Figure 5). The near-vertical sea cliff rises to elevation 24 to 26 feet. The bluff rises at a slope angles of 43 to 50 degrees to an elevation of 72 to 88 feet. Sea caves extend up to 16 feet into the cliff.

Comparison of the 1990 and 1998 topographic profiles in Cross Sections 3 through 10 suggests an average 6 feet of retreat of the sea cliff in the last eight years, varying from zero at 417 Pacific Avenue (south of the sea cave) to 15" feet at 261 Pacific Avenue. Photo 13 shows extensive overhangs below 235-241 Pacific Avenue, like those that formed as a precursor to the block falls that occurred immediately to the north. Accelerated subaerial erosion affects nine areas of marine terrace deposits along the bluff. Active over-bluff drainage appears to descend from beneath the gunnite slope surfacing below 235 Pacific Avenue.

During the 1982-83 storm season, the sea cave below 417/423 Pacific Avenue enlarged somewhat, with a partial roof collapse of the seaward overhang undermining upwards of 10 feet of the upper terrace deposits, leaving a fresh scar at the base of the sloping upper bluff, similar in appearance to the numerous other scars in this reach today. Based on discussions with Mr. Folgner, the owner at 417 Pacific Avenue, the scar at the base of the upper sloping bluff remained relatively stable for the first 8 to 10 years, with upper bluff failures eventually propagating up the face of the upper bluff, ultimately resulting in 4" feet of upper bluff retreat and the resulting upper bluff scar visible in Photo 4 today.

The sea cave, below 417/423 Pacific Avenue was unsuccessfully filled during this past year's storm season. The concrete infill appears to have been undermined, thus allowing it to settle and pull away from the roof. Erosion and flanking of this sea cave infill may have also been aggravated by the formation of edge waves traveling along the face of the infill, impacting upon and eroding the sidewalls of this relatively large sea cave. Sea cave and/or notch infills extend from 265 to 309 Pacific Avenue and 367 to 407 Pacific Avenue. These infills appear to have been successful, except below 269 Pacific Avenue, where an active block fall is in progress. Installations intended to mitigate subaerial erosion of the upper bluff include gunite at 235 Pacific Avenue, Jute matting at 245 and 327 Pacific Avenue, plastic sheeting at 301 Pacific Avenue, and post and board soil retainers at 325 Pacific Avenue.

6.5 Reach 5 - 231 to 139 Pacific Avenue

Reach 5 is characterized by a bedrock shore platform having no sand or shingle cover. Although block falls have not yet occurred, the sea cliff is severely undermined by notches and sea caves. The undermined areas are subject to failure at any time. The reach is shown in Map and Photo 6 and 7, and represented by Cross Section 11 at 211 Pacific Avenue, Figure 23. Photo 14 shows the extent of notching in this area in April 1998, prior to the removal of the emergency riprap and subsequent infill with the summer beach.

Throughout the majority of this reach, no beach exists. However, locally, below the lot at 231 Pacific Avenue, where past faulting has resulted in a step in the coastline, a 20-foot-wide beach currently exists. Small areas of shingle beach exist along the base of the cliff up to elevation 5 feet. Offshore, the bedrock shore platform is exposed. The near-vertical sea cliff rises to elevation 26 feet. The bluff rises at a typical slope angle of 44" degrees to an elevation of 84 to 89 feet. Sea caves extend up to 18 feet into the cliff, which consists of Torrey Sandstone. Deep notches and overhangs affect this reach (Table 3).

Comparison of the 1990 and 1998 topographic profiles in Cross Section 11 suggests the westerly-most limit of the sea cliff has not yet retreated along most of this reach. Accelerated subaerial erosion and active over-bluff drainage is absent from the upper bluff. A sea-cave infill below 201 Pacific Avenue has been flanked by deepening of the notch on both the north and south. The deep notches and overhangs could collapse at any time, producing high vertical scarps in the overlying marine terrace deposits, thus creating severe conditions like those at Reach 4.

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6.6 Reach 6 - Fletcher Cove

Fletcher Cove is bounded by the north and south sides of an ancient canyon, and a bluff of unconsolidated canyon fill and marine terrace. The Torrey Sandstone, which usually forms the near-vertical sea cliff is replaced by a Pleistocene-age canyon fill along this reach. The reach is shown in Map and Photo 7 and 8. Average beach widths within the cove range from 40 to 60 feet.

6.7 Reach 7 - Las Brisas

The Las Brisas reach is characterized by a large block fall, and extensive notching of the near-vertical sea cliff. The undermined areas are subject to failure at any time. The reach is shown in Map and Photo 6 and 7, and represented by Cross Sections 12 and 13, Figures 24 and 25.

The sand beach is almost nonexistent and extends up to elevation 3 feet at the base of the sea cliff in the overhang. Small areas of shingle beach exist along the base of the cliff. Offshore, the shore platform appears to have a thin, discontinuous layer of sand. The near-vertical sea cliff rises to elevation 26 feet. The bluff rises at a slope angle of 39" degrees to an elevation of 84 feet. A sea-cave infill is being flanked by erosion of the cliff on both sides.

Comparison of the 1990 and 1998 topographic profiles in Cross Section 12 and 13 suggests the block falls during the El Niño of 1997-98 account for all of the sea-cliff retreat since 1990. Cross Section 12, at the block fall, indicates 7 feet of retreat, creating an 8.3-foot high oversteepened scar in the overlying marine terrace deposits. Cross Section 13, only 37 feet north but outside the block fall indicates no measurable change since 1990.

The deep notches and overhangs could collapse at any time, producing high vertical scarps in the overlying marine terrace deposits, thus creating severe conditions like those at Reach 4.

7 COASTAL RETREAT OF THE SOLANA BEACH REGION

Before anthropic changes in the 20th Century, the coastal bluffs retreated in accordance with long-term sea-level rise since the last glacial maximum. By approximately 6,000 years ago, sea level had rapidly risen to within 12 to 16 feet of the present level. The rate then slowed by an order of magnitude to approximately 0.002-foot per year from an earlier rate of 0.028-foot per year. The configuration of the bluffs was similar to the pre-anthropic configuration throughout the more recent period of slow sea level rise, consisting of a transient sandy beach, seacliffs and upper bluffs. Using this history of sea level rise, the geologic retreat rate before anthropic changes can be estimated by finding the distance on the shore platform between the base of the sea cliff and the 12- and 16-foot depth contours. Where the base of seacliff is below sea level, an assumption is made that the same condition existed 6,000 years ago. Using the 14-foot depth contour (2 feet below sea level at the time), and 900 feet of bluff retreat in the last 6,000 years, results in an annualized bluff retreat rate of 0.15 foot per year.

Retreat of the coast may occur gradually, at a relatively uniform rate, or episodically, in large increments, followed by long periods of little or no retreat. Gradual retreat is well represented by annualized retreat rates; however, the annualized rates do not adequately describe the nearly instantaneous retreat of several feet or tens of feet that may occur episodically. As used in this study, annualized rates include the long-term effect of episodic retreat by averaging with the intervening periods of slow retreat.

The effect of an instantaneous episode of rapid retreat is a new configuration of part of the bluff that would not have been reached for years or decades by gradual retreat. Unaffected parts of the bluff must catch up to the new configuration before the episode is likely to recur. This concept is illustrated in Figure 26. For example, block failure into a notch along vertical bluff-parallel joints will not recur until the notch reforms and weathering loosens the next joint. In this section, the annualized rates of marine erosion of the seacliff and subaerial erosion of the bluff top are established, followed by estimates of episodic retreat from various mechanisms.

7.1 Marine Erosion of the Seacliff

The annualized rate of marine erosion of the seacliff has increased over the long-term geologic rate since the sand beach was lost. The rate of marine erosion of the seacliff has at least doubled along the entire Solana Beach coast as a result of loss of the sand beach. The most likely current rate of sea-cliff erosion is approximately 0.4-foot per year, obtained from analysis relating beach width to erosion rate (Everts, 1991). This rate is about double the long-term rate obtained from geologic analysis, 0.15-foot per year; however, it is consistent with the current best-guess rate derived from of sea-level rise (0.33 to 0.41 foot per year). All of these long-term rates are far higher than the 0.05-foot per year rate indicated by measurement of the sea cliff from 1970 to 1976 (Lee and others, 1976), when the beach was wide and the wave environment benign. The rapid erosion rates experienced during the 1997-98 El Niño are more consistent with the 0.4-foot per year long-term rate we estimate is currently affecting the Solana Beach coast. Erosion during the last season also is the primary component of the retreat measured from comparison of our 1998 topographic survey to the City of Solana Beach maps prepared from 1990 aerial photographs. Remember also that the 0.4 foot per year is measured to the back of any notch which would then manifest itself as recognizable sea cliff retreat after collapse of the notch.

Wherever part of a reach is protected by a seawall or revetment, marine erosion of the seacliff is arrested as long as the shore protection is maintained and was properly designed and constructed. However, where the seacliff extends above the seawall or revetment, it will be subject to subaerial processes that will likely cause very slow retreat at a rate on the order of 0.02 to 0.05 foot per year.

7.2 Subaerial Erosion of the Upper Bluff

When averaged over thousands of years, seacliff and bluff-top erosion rates will be equal. However, after say a century of storm quiescence, when the seacliffs experience little or no erosion, bluff tops having no partially cemented cap of beach ridge deposits will continue to retreat as the sloping bluff matures and its slope becomes flatter (see Figure 11). Conversely, after a period of intense storm activity, an increase in marine erosion will result in a temporary lag in bluff-top erosion due to the available (sacrificial) gentle sloping bluff that must now be eroded prior to again encroaching on the top of the bluff (see Figures 10 and 11). The presence of a partially-cemented cap, as exists along most of the study area, provides additional upper-bluff stability by protecting the underlying more-erodible marine terrace deposits, allowing them to maintain a steeper equilibrium slope in balance with long-term erosion of the sea cliff and partially cemented cap.

After an increase in marine erosion of the sea cliff severe enough to cause block falls extending up into the marine terrace deposits, headward erosion of the oversteepened bluff can undermine the partially cemented cap, causing the outer few feet to collapse. The susceptibility to undermining and collapse would continue until the original equilibrium slope is reestablished.

Historical data suggests that many years of severe coastal storm activity eroded coastal bluffs in the late 1800s. A hiatus in coastal storm activity allowed the coastal bluffs to equilibrate since then, with more severe wave energy again reported since 1980. This reduction in wave energy during the first 75" years in the 20th Century has allowed more mature, gentler slopes to develop. Thus, in predicting annualized bluff-top erosion rates for the next 50 years in areas without block falls, the more mature, gently-sloping upper bluff will at least temporarily lag ongoing seacliff erosion. For areas with block falls, the bluff-top rate will be higher during the next few years, approaching that of the lower sea cliff as the partially-cemented cap is undermined until the slope returns to its previous equilibrium.

7.3 Upper-Bluff Stability

Where residences have been constructed on the bluffs, information is often needed concerning surficial slope stability. The stability of slopes steeper than 50 degrees is difficult to demonstrate under normal practice in geotechnical engineering. Soil strength used in stability analyses is from laboratory tests of saturated soil. Saturation weakens the intergranular structure on which the upper bluff sediments depend to stand at inclinations over 50 degrees. This practice recognizes the likelihood that subsurface soils will become wet from irrigation of vegetation, rainfall or groundwater migration (USCOE, 1996).

Where marine erosion allows a fairly rapid retreat of the lower bedrock unit (primarily by block falls along joints and faults within the various middle Eocene-age units), the upper-bluff Pleistocene sands are undermined, causing a relatively steep to near-vertical upper bluff, more susceptible to continuous sloughing. Traditional engineering stability analyses have only limited usefulness for this type of profile, because the upper bluff terrace sands continually slough and ravel to re-attain a stable angle of repose (a natural geomorphic process). This natural geologic "flattening" process reduces the driving force from a hypothetical failure geometry, and renders the original stability analyses invalid. Further, marine erosion at the seacliff continues to undermine the upper bluff from the basal contact up, starting the whole process over again. In summary, and from a practical standpoint, proper determination of the appropriate bluff-top setback must include an analysis of both the rate of marine erosion of the lower cliffed portion of the bluff, and of the effect of that rate in creating an "artificially" oversteepened upper bluff.

7.4 Bluff-Top Failures

For given values of soil strength, and assuming homogeneous conditions within the geologic units, the stability of the bluff top can be shown to be a function of the slope and the thickness of the upper terrace deposits, along with the height of a vertical scarp in the terrace deposits at the Eocene contact. The development of a vertical scarp at the base of the terrace deposits above the Eocene contact occurs subsequent to the development and collapse of a notch at the base of the seacliff. Assuming a 45 degree upper slope inclination, the failure of a ten-foot-deep notch in the Eocene unit results in a ten-foot vertical scarp above the contact.

In order to assess the stability of the upper bluff, slope stability analyses were performed using soil strengths for the upper terrace deposits as follows (USCOE, 1996):

$$\varphi = 33 \text{ degrees}$$
$$c = 300 \text{ psf}$$
$$\gamma_t = 124 \text{ pcf}$$

A terrace thickness of 50 feet was analyzed for various slope inclinations and lower vertical scarp heights. The results are reported on Figures 27 and 28. Critical failure geometries

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were evaluated, specifically addressing the distance to the failure scarp from both the top-of-slope and from the face of the lower near-vertical seacliff. Factors of safety are also shown for the various slope geometries. Recognizing that upper bluff failures propagate in much the same fashion as that shown on Figure 10, slope geometries exhibiting factors of safety greater than 1.25 should be viewed as unsusceptible to upper-bluff failures. Recognizing also that progressive collapse of the bluff top is episodic in nature, only those areas where relatively steep upper bluffs currently exist are susceptible to bluff-top collapses, triggered by either progressive marine erosion undermining the lower seacliff, or from other subaerial factors.

8 SHORELINE AND COASTAL BLUFF PROTECTION

The progressive loss of the transient sand beach, resulting from the cumulative effects of sand removal in the urbanizing coastal watershed, has caused a dramatic increase in the rate of marine erosion, with the majority of the study area experiencing upwards of 8 to 10 feet of retreat in the last 15 years. Marine erosion has typically manifested itself in the formation of sea caves and/or notches, where the notch or overhang eventually collapses once it extends beyond bluff-parallel fractures in the Torrey Sandstone, typically on the order of 6 to 10 feet back from the face of the cliff. Although the formation of sea caves may appear to be more problematic, they have more inherent stability than the notch due to their arching effect. The notch without the benefit of any subjacent lateral support shears off as a large slab, as has occurred throughout the majority of Reach 4. Significant failures within the lower sea cliff have undermined and destabilized the base of the upper sloping terrace deposits, with some of the worst upper-bluff failures below the lots at 261, 367, and 371 Pacific Avenue. Elsewhere, where significant notches still remain, as in the vicinity of 205 to 231 Pacific Avenue, and 235 to 265 Pacific Avenue, additional failures will further destabilize the upper bluff (as in the vicinity of 255 to 265 Pacific Avenue) and otherwise destabilize an area that is currently relatively stable (211 through 231 Pacific Avenue).

The 1997-98 El Niño storm season has caused significant erosion of the coastal bluff throughout the study area; however, a serious problem still remains. With the almost total loss of the protective sand beach in this area, these sea cliffs continue to experience a limited amount of marine erosion on a daily basis due to both direct wave impact and cobble abrasion, which will eventually result in additional bluff failures. If left unabated, these bluff failures will eventually encroach upon existing bluff-top improvements, substantially degrading the visual character of the coastline and ultimately resulting in a similar situation to that in Leucadia just north, where coastal stabilization, allowed by the Coastal Act to protect structures, has significantly adversely affected the character of that coastal community.

Since the actual failure of the vertical bluff is associated with a progressive loss of shear strength within the bluff-parallel fracture, these failures can occur at any time, unassociated with high wave activity. This results in a very real public safety concern in that the bluff can fail literally at any time of the day, even during tidal lows when the public may be walking along the beach.

As indicated in the California Coastal Act, as well as in the City of Solana Beach's Municipal Code, any future coastal protection should minimize shoreline encroachment, should be designed to minimize the alteration of natural landforms, and must be visually compatible with the character of the surrounding coastal bluffs. Properly designed coastal protection measures can be designed to enhance the visual quality in certain areas, while improving public safety and, thus, utilization of the coastline. Both the City of Solana Beach and the California Coastal Commission recognize that some level of pro-active coastal protection is in the best interests of both the bluff-top homeowners and the citizens of Solana Beach, as well as other members of the public that recreate on this beach. Although it is the City's policy to discourage use of seawalls, as stated in Section 17.62.020 of the Solana Beach Municipal Code, it is the City's policy to approve measures to stabilize caves, joints, faults, ruptures, or cracks in the bluff surface. As indicated in the Solana Beach Municipal Code, these infills are considered acceptable as a reasonable measure to prevent erosion and minimize effects that could result in a future need to construct a more intrusive protection device.

As indicated in Section 17.62.100 of the City's Municipal Code, filling sea caves or other geologically hazardous conditions affecting the bluff surface may be approved when it is determined that the infill is:

1. A necessary preventative measure to stop erosion from enlarging the cave, crack, fissure, joint, or fault, which, if enlarged, would eventually threaten the stability of the bluff; or

2. Necessary to protect structures on top of the bluff threatened by the collapse of a cave large enough to impair bluff stability; or

3. Necessary to eliminate an actual public nuisance, including, without limitation, an attractive nuisance.

Clearly, all three of these conditions are satisfied.

Recognizing that no remedial work will result in significant additional coastal bluff erosion, necessitating significant and costly structures to protect the bluff-top residences (as allowed by Section 30235 of the California Coastal Act), it would appear to be in the best interest of the bluff-top owners and public alike to implement infills of both sea caves and notches in accordance with the applicable conditions contained in the Solana Beach Municipal Code. We suggest that both sea caves and notch infills be completed in general accordance with the design criteria provided on Figure 29 . This would incorporate an erodible concrete infill that could be carved and colored to blend into that of the adjacent natural sea cliff.

8.1 Beach Nourishment

Wide, protective sand beaches are clearly the most efficient form of shoreline protection and particularly well suited for the Solana Beach area in view of the relatively fragile, coastal bluffs. Simply stated, a sufficiently wide beach would not allow waves to impact directly upon the coastal bluffs. Severe storms will, however, displace considerable sand, thus the need for a sufficiently wide sacrificial cross section of beach to allow erosion and displacement of the transient sandy beach materials. The Resources Agency of the State of California (1997) and SANDAG's Shoreline Preservation Strategy (1993) recognize that beach renourishment is by far the best approach to shoreline protection. SANDAG has championed the use of opportunistic sand for beach nourishment, recognizing that beach nourishment provides both increased shoreline protection and recreational benefits. The state of California's tourism industry currently generates about $10 billion in annual revenues, with most of the state's tourism driven by coastal-related industries (San Francisco State University, 1997). An ongoing commitment to beach nourishment and capitalizing on available opportunistic sand sources will reduce coastal bluff erosion and provide recreational beach opportunities that benefit the entire community.

Although a healthy beach nourishment project can essentially eliminate future shoreline erosion, the reality is that 25+ million cubic yards of sand is necessary within the Oceanside littoral cell to protect against storm-induced erosion. This sand would develop a 200+ foot wide recreational/protective sand beach and recharge the nearshore sand volume out to the seaward limit of reversible sediment movement (the "v" in the Coastal Commission's Sand Mitigation fee equation). This level of required protective beach nourishment would cost in excess of $125 million, along with an additional annualized renourishment cost on the order of $2.5 million (320,000-cubic yards per year at $8/cubic yard). The likelihood of this level of protective sand beach being in place prior to additional bluff failures within Solana Beach is quite low and interim measures are necessary to protect these fragile coastal bluffs from failures that would otherwise occur, significantly altering the visual character of this coastal community prior to any long-term beach renourishment program. The value of protective/recreational sand beaches cannot be overemphasized, and this clearly represents the best long-term solution for protecting the quality of this valuable natural resource for both the bluff-top homeowners and the community of Solana Beach.

TABLE 1

GRAIN SIZES FOR VARIOUS NATURAL IMPORTED BEACHES IN SAN DIEGO COUNTY

U.S. Std. Sieve Size	Grain Size (mm)	Coronado Beach VB Courts	South Mission Beach VB Courts	La Jolla Shores VB Courts	San Dieguito Beach	Fletcher Cove Beach	Cardiff State Beach	Swami's Beach Access	Moonlight Beach VB Courts (imported)	Batiquitos Lagoon Beach VB Court (dredged)	Encinas Creek Beach VB Court (dredged)	Encinas Creek Inlet (imported) "Red Sand"	Agua Hedionda Beach (dredged)	Carlsbad Seawall Beach (dredged)	Oceanside Buccaneer Beach
4	4.76	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
7	2.83	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	98.7%	98.5%	100.0%	99.7%	100.0%	100.0%
10	2	100.0%	100.0%	100.0%	100.0%	100.0%	99.9%	100.0%	99.6%	98.3%	98.0%	100.0%	99.5%	99.8%	100.0%
14	1.41	100.0%	100.0%	100.0%	100.0%	100.0%	99.8%	100.0%	98.1%	97.7%	97.5%	99.9%	99.2%	99.4%	100.0%
18	1	100.0%	99.8%	100.0%	100.0%	100.0%	99.6%	100.0%	94.1%	96.9%	96.7%	99.5%	98.9%	98.9%	100.0%
25	0.71	100.0%	99.6%	100.0%	99.9%	100.0%	99.3%	99.9%	83.3%	94.9%	94.5%	97.1%	98.0%	98.1%	100.0%
35	0.5	99.8%	98.1%	100.0%	99.8%	99.9%	98.3%	99.7%	58.0%	87.4%	87.1%	82.1%	94.4%	95.5%	99.9%
45	0.35	97.9%	88.5%	99.9%	99.3%	99.7%	95.5%	97.9%	30.7%	76.5%	75.9%	59.1%	79.4%	85.4%	96.4%
60	0.25	78.1%	42.9%	97.7%	82.2%	93.6%	69.1%	73.1%	13.6%	51.2%	49.0%	39.3%	47.5%	53.1%	62.3%
80	0.177	35.2%	12.7%	57.0%	36.4%	71.7%	25.7%	29.4%	6.3%	21.5%	20.8%	29.4%	23.3%	23.3%	23.9%
120	0.125	6.3%	2.7%	17.1%	9.5%	33.4%	5.9%	7.9%	2.6%	4.5%	4.7%	23.5%	5.1%	7.3%	5.2%
170	0.088	1.5%	0.7%	3.4%	2.1%	4.7%	1.2%	1.6%	1.1%	4.5%	1.5%	21.2%	2.0%	2.4%	1.0%
200	0.074	0.6%	0.4%	1.0%	0.6%	0.4%	0.5%	0.8%	0.8%	0.9%	0.8%	20.4%	1.2%	1.5%	0.6%
	D(60)	0.22	0.29	0.18	0.21	0.16	0.23	0.23	0.52	0.28	0.29	0.36	0.29	0.27	0.25
	D(50)	0.20	0.27	0.17	0.20	0.15	0.22	0.21	0.46	0.25	0.25	0.30	0.26	0.24	0.23
	D(30)	0.17	0.22	0.14	0.16	0.12	0.18	0.18	0.35	0.20	0.20	0.18	0.20	0.19	0.19
	D(10)	0.13	0.16	0.11	0.13	0.09	0.14	0.13	0.23	0.14	0.14	NA	0.14	0.13	0.14
	Phi(50)	2.31	1.91	2.57	2.33	2.76	2.20	2.24	1.13	2.02	1.98	1.72	1.95	2.04	2.14
Uniformity Coefficient, Cu		1.66	1.76	1.72	1.70	1.70	1.73	1.75	2.26	2.01	2.05	NA	2.08	2.03	1.78
Curvature Coefficient, Cc		0.97	1.02	1.04	1.00	0.95	1.07	1.07	1.01	0.97	0.98	NA	0.97	1.03	1.05
USCS (ASTM)		SP	SP	SP	SP	SP	SP	SP	SP	SP	SP	SM	SP	SP	SP
Munsell Color		2.5Y 6/1	2.5Y 6/2	2.5Y 5/1	2.5Y 5/1	2.5Y 4/1	2.5Y 7/1	2.5Y 6/1	2.5Y 7/1	2.5Y 7/2	2.5Y 6/1	5 YR 4/4	2.5Y 6/1	2.5Y 6/1	2.5Y 5/1
		Gray	Light brownish gray	Gray	Gray	Dark gray	Light gray	Gray	Light gray	Light gray	Gray	Reddish brown	Gray	Gray	Gray

[Reproduced from Woodward-Clyde Consultants, 1998]

TABLE 2

Hindcast (1900-84) Waves Exceeding 3 m Height Near 35EN
(Seymour et. al., 1984)

EXTREME WAVE EPISODES EXCEEDING 3 M. (BASIC SERIES)
1900 - 1984

DATE	SIG. HT. (m)	MAX. PERIOD	DIRECTION
13 MAR 05	8.8	15	247
17 NOV 05	3.3	17	286
31 DEC 07	5.3	16	282
12 MAR 12	3.2	12	220
26 JAN 14	5.8	13	223
03 FEB 15	7.5	14	235
01 JAN 18	3.7	16	280
12 FEB 19	5.3	12	299
20 DEC 20	4.7	13	301
15 OCT 23	3.7	16	296
01 FEB 26	6.9	15	257
03 JAN 27	5.8	20	287
06 NOV 28	4.0	17	294
01 JAN 31	3.9	16	276
28 DEC 31	7.4	18	288
19 DEC 35	4.7	16	267
13 DEC 37	4.5	16	272
06 JAN 39	7.9	19	285
25 SEP 39	4.5	15	205
24 JAN 40	4.3	16	267
25 DEC 40	5.7	16	270
20 OCT 41	3.3	17	294
30 DEC 45	3.9	19	285
13 FEB 47	3.9	16	265
04 NOV 48	4.7	18	300
15 NOV 53	5.7	17	269
15 JAN 58	3.1	22	280
26 JAN 58	6.8	14	259
05 APR 58	7.7	18	289
16 FEB 59	5.1	14	244
09 FEB 60	8.1	19	295
22 DEC 60	3.4	17	276
31 JAN 63	4.2	16	260
10 FEB 63	5.9	15	256
19 NOV 65	4.0	15	277
07 DEC 67	4.0	15	298
06 FEB 69	4.7	13	222
04 DEC 69	3.6	17	278
06 DEC 69	4.9	22	274
14 DEC 69	5.7	17	290
19 DEC 69	4.7	18	281
26 DEC 72	4.1	15	289
21 FEB 77	5.2	18	280
29 OCT 77	5.5	20	299
16 JAN 78	6.0	13	240
01 JAN 80	4.7	20	272
17 FEB 80	6.1	18	249
22 JAN 81	4.3	20	258
28 JAN 81	7.0	17	262
13 NOV 81	4.9	18	284
01 DEC 82	6.4	14	295
18 DEC 82	6.4	20	288
25 JAN 83	6.1	17	278
27 JAN 83	7.3	22	279
10 FEB 83	6.7	25	281
13 FEB 83	4.9	17	268
01 MAR 83	8.2	20	258
14 NOV 83	5.0	17	290
03 DEC 83	7.0	17	285
25 FEB 84	6.4	17	300

TABLE 3
COMPILATION OF MEASUREMENTS
SEA CAVES, NOTCHES, OVERHANGS

		Depth of Sea Caves, Notches and Overhangs			Upper Bluff Slope Inclination				
Address	Sea Cave	Notch Depth (ft)	Overhang (ft)	Cave Depth (ft)	Overall Before 97/98 (degrees)	Overall After 97/98 (degrees)	Lower Steep'nd (degrees)	Retreat of Vertical Lower Cliff Since 1990 (ft)	Lower Cliffed Interval of Terrace Deposits (undermined by marine erosion, ft)
REACH 7 - LAS BRISAS									
South of LB			4.8						
South of LB		9.0							
Las Brisas	X			15.0	38	47	79	7.0	8.3
					39	39			
REACH 6 - FLETCHER COVE									
REACH 5 - 139 TO 321 PACIFIC									
141/197	X			32.0					
197			3.8						
201		6.4	10.8						
	X			18 - partial					
205/211	X			11.3	44	44			
211			8.5						
231	X			Filled					
REACH 4 - 235 TO 475 PACIFIC									
235/241			8.9						
245/249			3.2						
261					47	60	80	15.5	24.5
265	X			Filled					
269					43	43		4.0	
265-309	XXX			Filled					
301					45	47	89	4.0	9.3
309					44	49	87	10.0	
311/319			6.8						
325/327		2.9	5.0						
333		2.8	5.8						
337					43	43		1.5	

Measured sea cave and notch depths reflect conditions in June and July 1998, after the seasonal onshore movement of sand had covered the bottom and rear portions of the abrasion features. Therefore, the depths reported in this table likely underestimate the actual depths of notches and sea caves.

TABLE 3
COMPILATION OF MEASUREMENTS
SEA CAVES, NOTCHES, OVERHANGS

		Depth of Sea Caves, Notches and Overhangs			Upper Bluff Slope Inclination			Retreat	Lower Cliffed
Address	Sea Cave	Notch Depth (ft)	Overhang (ft)	Cave Depth (ft)	Overall Before 97/98 (degrees)	Overall After 97/98 (degrees)	Lower Steep'nd (degrees)	of Vertical Lower Cliff Since 1990 (ft)	Interval of Terrace Deposits (undermined by marine erosion, ft)
337/341		2.8	5.8						
347		3.1							
355	X			15	43	49	90	6.0	4.5
357	X	1.8		15					
367	X			Filled					
371	XX			Filled	53	53		7.0	
403	XX			Filled					
407	XX			Filled					
417/423	X			16 - partial	49	53	68	0*	*southerly of the sea cave
475	X			16					
REACH 3 - TIDE PARK		2.9							
REACH 2 - 517 TO 525 PACIFIC									
517	XX			Filled					
521	X			Filled					
525	XXXX	3.0		Filled					
		2.4							
		3.4							
529	X			Filled	41	41		4.5	
	X			?					
533	XX			?					
REACH 1 - 533 PACIFIC TO CARDIFF STATE BEACH									
601	X			?					
611	X			?					
617					37	37			
633	X	2.2		10.0				19.0	
	Average	3.6	6.3	16.5	44	47	82	7.9	11.7
	Maximum	9.0	10.8	32.0	53	60	90	19.0	24.5
	Minimum	1.8	3.2	10.0	37	37	68	0.0	4.5

Measured sea cave and notch depths reflect conditions in June and July 1998, after the seasonal onshore movement of sand had covered the bottom and rear portions of the abrasion features. Therefore, the depths reported in this table likely underestimate the actual depths of notches and sea caves.

REFERENCES

1. Barry, R.G., 1981, Trends in snow and ice research, EOS 62, 46, p. 1139-44.

2. Bird, Eric C.F., 1985, Coastline changes, a global review: John Wiley & Sons.

3. Bradley, W.C., and Griggs, G.B., 1976, Form, Genesis and Deformation of Central California Wave-cut Platforms. Geological Society of America Bulletin, Volume 87, Pages 433 - 449, 16 Figures.

4. Brunn, P., 1962, Sea-level rise as a cause of shore erosion, J. Waterways and Harbors Div. ASCE 88:117-130.

5. Brunn, P., 1954, Coastal erosion and development of beach profiles, Beach Erosion Board Technical Memorandum NO. 44, Washington, D.C.: U.S. Army Corps of Engineers.

6. Crowell, M.; Leatherman, S.P.; and Buckley, M.K., 1991, Historical Shoreline Change - Error Analysis and Mapping Accuracy. Journal of Coastal Research, 7 (3), Pages 839 - 852. Ft. Lauderdale, Florida.

7. Curray, J.R., 1965, Late Quaternary history; continental shelves of the United States, p. 723-735 in H.E. Wright, Jr. and D.G. Frey (eds), The Quaternary of the United States, Princeton Univ. Press, 922 p.

8. Curray, J.R., 1960, Sediments and history of Holocene transgression, continental shelf, northwest Gulf of Mexico, p. 221-266, in F.P. Shepard, F.B. Phlefer, and Tj.H. van Andel (eds), Recent Sediments, Northwest Gulf of Mexico, 1951-1958, Amer. Assoc. Petroleum Geologists, Tulsa, Oklahoma, 394 p.

9. Curray, J.R., 1961, Late Quaternary sea level: a discussion. Geological Society of America Bulletin 72, p. 1707-12..

10. Emery, K.O., and Kuhn, G.G., 1982, Seacliffs: Their Processes, Profiles and Classification. Geologic Society of American Bulletin, Volume 93, Number 7, Pages 644 - 654, 8 Figures.

REFERENCES
(continued)

11. Emery, K.O., and Aubrey, D.G., 1991, Sea Levels, Land Levels and Tide Gauges. Springer-Verlag Publishers, New York, NY, 237 Pages, 113 Figures.

12. Everts, Craig H., 1991, Seacliff Retreat and Coarse Sediment Yields in Southern California. Proceedings, Coastal Sediments '91, Specialty Conference/WR Div./ASCE, Seattle, WA/June 25-27, 1991, Pages 1586 - 1598.

13. Fenneman, M.M., 1902, Development of the profile of equilibrium of the subaqueous shore terrace. J. Geol. 6(4):532-545.

14. Fisher, P.J., and Mills, G.I., 1991, The Offshore Newport-Inglewood-Rose Canyon Fault Zone, California: Structure, Segmentation and Tectonics. In Environmental Perils - San Diego Region. (ed.) P.L. Abbott and W.J. Elliott. Published by San Diego Association of Geologists, Pages 17 - 36.

15. Fleet Numerical Oceanography Center, 1987, Spectral ocean wave model (SOWM), preparation of hindcasts for Moffatt & Nichol, Engineers.

16. Flick, R.E. and D.R. Cayan, 1984, Extreme sea levels on the coast of California, Proceedings of 19th Coastal Engineering Conference, Pages 886-898.

17. Fulton, K., 1981, A Manual for Researching Historical Coastal Erosion. G.G. Kuhn, ed. Manual Describes Methodology Developed by Kuhn for Researching Historical Database to Document Coastal Changes; California Sea Grant Report Number T-CSGCP-003, 56 Pages, 29 Figures, 2 Appendices.

18. Group Delta Consultants, Inc., 1993, Shoreline Erosion Evaluation, Solana Beach Coastline, San Diego County, California.

19. Hands, E.B., 1983, The Great Lakes as a test model for profile response to sea level changes. Pp. 167-189 *in* CRC Handbook of Coastal Processes and Erosion Control. Boca Raton, Fla.: CRC Press.

20. Hands, E.G., 1981, Predicting adjustments in shore and offshore sand profiles on the Great Lakes. CETA 81-4. Vicksburg, Miss.: Coastal Engineering Research Center. 25 pp.

REFERENCES
(continued)

21. Hands, E.B., 1976, Observations of barred coastal profiles under the influence of rising water levels, Eastern Lake Michigan, 1967-1971. TR-76-. Vicksburg, Miss.: Coastal Engineering Research Center.

22. Horrer, P., 1960, Southern hemisphere swell and waves from a tropical storm at Long Beach, California: Beach Erosion Board Bulletin, v. 4, no. 1, 18 p.

23. Howell, D.G., Stuart, C.G., Platt, J.P., and Hill, D.J., 1974, Possible Strike-slip Faulting in the Southern California Borderland. Geology, Volume 2, Number 2, Pages 93 - 98.

24. Inman, D.L., 1976, Summary Report of Man's Impact on the California Coastal Zone. Prepared for the Department of Navigation and Ocean Development, State of California, 150 Pages.

25. Inman, D.L., and Bagnold, R.A., 1963, "Littoral Processes. Pages. 529 - 553, in M.N. Hill (ed.) The Sea, Volume 3, The Earth Beneath the Sea, Interscience. John Wiley & Sons, New York, London, 963 Pages.

26. Inman, D.L., and Veeh, H.H., 1966, Dating the 10-fathom terrace off Hawaii. American Geophysical Union, Trans. 47, 125.

27. Kennedy, M.P., and Peterson, G.L., 1975, Geology of the San Diego metropolitan Area, California: Del Mar, La Jolla, Point Loma, La Mesa, Poway and SOUTHWEST ¼ Escondido 7½ minute quadrangles, California Div. of Mines and Geology, Bulletin 200, Sacramento, 56 p. & plates.

28. Kern, J.P., 1977, Origin and History of Upper Pleistocene Marine Terraces, San Diego, California. Geological Society of America, Bulletin 88, Pages 1553 - 1566.

29. Kuhn, G.G., and Shepard, F.P., 1985, Dana Point to the Mexican Border. In Living with the California Coast, Griggs, G.L., and Savoy, L., eds., Duke University Press, Durham, N.C., Chapter 18, Pages 344 - 393.

REFERENCES
(continued)

30. Kuhn, G.G., and Shepard, F.P., 1984, Seacliffs, Beaches and Coastal Valleys of San Diego County. Some Amazing Histories and Some Horrifying Implications: University of California Press, Berkeley, California, and London, England, 193 Pages, 99 Figures.

31. Kuhn, G.G., and Shepard, F.P., 1983, Newly Discovered Evidence From the San Diego County Area of Some Principles of Coastal Retreat. Shore and Beach, Volume 51, Number 1, Pages 3 - 12.

32. Kuhn, G.G., and Shepard, F.P., 1980, Coastal Erosion in San Diego County, California. In Coastal Zone '80, Proc. of Second Symposium on Coastal and Ocean Management Held in Hollywood, Florida on 17 - 20 November, 1980. B.L. Edge, ed., Published by American Society of Civil Engineers, Volume III, Pages 1899 - 1918.

33. Kuhn, G.G., and Shepard, F.P., 1983, Newly discovered evidence from the San Diego County area of some principles of coastal retreat: Shore and Beach, v. 51, no. 1, p. 3-12.

34. Lajoie, K.R., Ponti, D.J., Powell II, C.L., Mathieson, S.A., Sarna-Wojcicki, A.M., 1992, Emergent Marine Strandlines and Associated Sediments, Coastal California; a Record of Quaternary Sea-Level Fluctuations, Vertical Tectonic Movements, Climatic Changes, and Coastal Processes, in The Regressive Pleistocene Shoreline, Coastal Southern California, Annual Field Trip Guide Book No. 20, South Coast Geological Society, Inc., pp. 81 - 104.

35. Lee, Louis, Pinckney, C.J., and Bemis, C., 1976, Seacliff Base Erosion, San Diego, California. American Society of Civil Engineers, National Water Resources and Ocean Engineering Conference, April 5 - 8, 1976, Preprint 2708, Pages 1 - 13.

36. Leighton and Associates, Inc., 1979, Geotechnical Investigation, Condominium Bluff Site, Southwest Corner of 4th and H Streets, Solana Beach, California. Project Number 479062-01. March 27, 1979.

37. Marine Advisers, 1960, Design waves for proposed small craft harbor at Oceanside, California, prepared for U.S. Army Corps of Engineers, Los Angeles District.

REFERENCES
(continued)

38. Marine Advisers, 1961, A statistical survey of ocean wave characteristics in southern California waters, prepared for the U.S. Army Corps of Engineers, Los Angeles District, Marine Advisers, Inc., La Jolla, CA, 30 p.

39. Marine Board, National Research Council, 1987, Responding to changes in sea level: engineering implications. National Academy Press, Washington, D.C.

40. Masters, P.M., and N.C. Fleming, 1983, Quaternary coastlines and marine archaeology: towards the prehistory of land bridges and continental shelves: Academic Press, New York, 641 p.

41. May, Karen D., October 1987, Historical chronology of extreme storm and wave events in San Diego County, prepared for Moffatt & Nichol, Engineers.

42. Meteorology International, Inc., 1977, Deep-water wave statistics for the California coast, Stations 5 and 6, prepared for the Department of Navigation and Ocean Development, State of California.

43. Munk, W.H., Miller, G.H., Snodgrass, F.E., and Barber, N.F., 1963, Directional recording of swell from distant storms. Phil. Trans. Roy Soc. London, A, v. 55, n. 1062, p. 505-584.

44. Munk, W.H., and Traylor, M.A., 1947, Refraction of ocean waves: a process linking underwater topography to beach erosion: Journal of Geology, v. LV, no. 1, p. 1-28, 17 figures, 9 plates.

45. National Oceanic and Atmospheric Administration, 1980, A climatology and oceanographic analysis of the California Pacific outer continental shelf region.

46. National Oceanic and Atmospheric Administration (NOAA), 1978, Tidal bench marks, La Jolla pier, San Diego County, 1960-1978, U.S. Department of Commerce, National Ocean Service.

47. National Marine Consultants, Inc., 1960, Wave statistics for seven deep water stations along the California coast. Prepared for the U.S. Army Corps of Engineers, Los Angeles District.

REFERENCES
(continued)

48. National Research Council, 1987, Responding to Changes in Sea Level, Engineering Implications. National Academy Press, Washington, D.C.

49. Nordstrom, C.E., and Inman, D.L., 1973, Beach and Cliff Erosion in San Diego County, California: In Studies on the Geology and Geologic Hazards of the Greater San Diego Area, California. A. Ross and R.J. Dowlen, Eds., Published by San Diego Association of Geologists and the Association of Engineering Geologists, Pages 125 - 132.

50. Pacific Weather Analysis, 1987, Preparation of tropical storm and southern swell hindcasts for Moffatt & Nichol, Engineers.

51. Pacific Weather Analysis, 1983, Preparation of extratropical storm wave hindcasts for Moffatt & Nichol, Engineers.

52. Quinn, W.H., D.O. Zopf, K.S. Short, and R.T.W. Kuo Yang, 1978, Historical trends and statistics of the southern oscillation, El Niño, and Indonesian droughts, Fisheries Bulletin, (76), 663-678.

53. San Diego Association of Governments, July 1993, Shoreline preservation strategy for the San Diego region.

54. San Francisco State University, May 1997, The economic value of California's beaches.

55. Seymour, R.J., Strange, R.R. III, Cayan, D.R., and Nathan, R.A., 1984, Influence of El Niños on California's wave climate. Proc. 19th Coastal Eng. Conf., Amer. Soc. Civil Eng., p. 577-592.

56. Seymour, R.J., 1989, Wave observations in the storm of 17-18 January 1988. Jour. of Amer. Shore and Beach Preservation Assn., v. 57, n. 4, p. 10-14.

57. Shackleton, N.J., and Opdyke, N.D., 1976, Oxygen-isotope and paleomagnetic stratigraphy of Pacific core V28-239, late Pliocene to latest Pleistocene, Geological Society of America, Memoir 145.

REFERENCES
(continued)

58. Shepard, F.P., and Grant, U.S. IV, 1947, Wave Erosion Along the Southern California Coast. Bulletin of the Geological Society of America, Volume 58, Pages 919 - 926. October 1947.

59. Shepard, F.P., and Kuhn, G.G., 1983, History of Sea Arches and Remnant Stacks of La Jolla, California, and Their Bearing on Similar Features Elsewhere. Marine Geology, 51, Pages 139 - 161.

60. State of California, The Resources Agency, March 1997, California's ocean resources: an agenda for the future.

61. Sunamura, T., 1977, A Relationship Between Wave-induced Cliff Erosion and Erosive Forces of Waves. J. Geol. 85, Pages 613 - 618.

62. Trenhaile, Alan S., 1987, The Geomorphology of Rock Coasts. Clarendon Press, Oxford, 384 Pages.

63. Turner, R.J., 1981, Ground Water Conditions in Solana Beach, California as They Relate to Seacliff Stability. Unpublished M.S. Thesis in Environmental Studies. Department of Geological Sciences, California State University, Fullerton, 81 Pages, 20 Figures, 2 Plates, 3 Tables.

64. U.S. Army Corps of Engineers, 1960, Beach erosion control report on cooperative study of San Diego County, California: ed. C.T. Newton, contract no. W-04-193-ENG.-5196, appendix IV, phase 2, 60 p., 8 plates, 8 appendices.

65. U.S. Army Corps of Engineers, 1989, Coast of California storm and tidal waves study, historic wave and sea level data report, San Diego region.

66. U.S. Army Corps of Engineers, 1988, Coast of California storm and tidal waves study, sediment budget report, Mission Bay Littoral Cell.

67. U.S. Army Engineer Waterways Experiment Station, 1987, Extremal significant Wave Height Distributions - Computer Program: WAVDIST (MACE-17), Coastal Engineering Technical Note I-40.

REFERENCES
(continued)

68. U.S. Army Corps of Engineers, 1987, Coastal Cliff Sediments, San Diego Region. Los Angeles District, Coast of California Storm and Tidal Waves Study, CCSTWS 87-2, June 1987, Prepared by Kuhn, Osborne.

69. U.S. Army Corps of Engineers, 1987, Shoreline movement investigations report, Portuguese Point to the Mexican Border (1852 - 1982). Los Angeles District, Coast of California Storm and Tidal Waves Study, CCSTWS 87-10, prepared by Kuhn, Osborne.

70. U.S. Army Corps of Engineers, 1988, Sand thickness survey report, October - November 1987, San Diego Region, CCSTWS 88-5, prepared by Tekmarine, Inc.

71. U.S. Army Corps of Engineers, 1987, Oceanside littoral cell, preliminary sediment budget report, CCSTWS 87-4, prepared by Tekmarine, Inc.

72. U.S. Army Corps of Engineers, 1988, Coastal cliff sediments, San Diego region, CCSTWS 88-8, prepared by Brain A Robinson & Associates.

73. U.S. Army Corps of Engineers, 1991, State of the coast report, San Diego region, CCSTWS, Vol. I - main report, Final - September 1991.

74. U.S. Army Corps of Engineers, March 1996, Encinitas shoreline, San Diego County, California, CCSTWS.

75. U.S. Coast and Geodetic Survey, 1887-88, Descriptive Report to Accompany Original Field Sheet, Entitled: Topography, Pacific Coast, Northward From San Dieguito Valley, California. Scale 1:10,000; National Ocean Survey Archives, 10 Pages.

76. Wallace, R.E., 1977, Profiles and Ages of Young Fault Scarps, North-Central Nevada. Geological Society of America Bulletin, Volume 88, Pages 1267 - 1281.

REFERENCES
(continued)

77. Warme, J.E., and Marshall, N.F., 1969, Marine Borers in Calcareous Terrigenous Rocks of the Pacific Coast. American Zoologist, Volume 9, Number 3, Edition 2, Pages 765 - 774.

78. Woodward-Clyde Consultants, April 21, 1998, Beach sand suitability analyses, Yuma sedimentation project, Yuma, Arizona.

MAPS

1. Continental Data Systems, Inc., 1971. Untitled Bathymetric Maps Extending From Mexican Border to Point Conception. Scale: 1:48,000.

2. County of San Diego, 1985. Untitled Orthotopographic Map Numbers 322 - 1677, 318 - 1677, 314 - 1677, 310 - 1683, 306 - 1683, 302 - 1683. Scale: 1:2,400. October 25, 1985.

3. County of San Diego, 1975 Untitled Orthotopographic Map Numbers 334 - 1671, 330 - 1671, 326 - 1671, 326 - 1677. Scale: 1:2,400. September 17, 1975,

4. County of San Diego, 1960. Untitled Topographic Map Numbers 334 - 1671, 330 - 1671, 326 - 1671, 326 - 1677, 322 - 1677, 318 - 1677, 314 - 1677, 310 - 1683, 306 - 1683, 302 - 1683. Scale: 1:2,400. July 1960.

5. Eisenberg, Leonard, 1983. Maps Found in On the Manner of Deposition of the Eocene Strata in Northern San Diego County, 1985, Plates 1 - 3. Scale: 1:24,000.

6. Fischer, Peter J., 1980. Southern California Margin Project, Geologic Map, Carlsbad to La Jolla. Scale: 1:24,000. April 15, 1980.

7. U.S. Army Corps of Engineers, 1985. Shoreline Movement Map, Solana Beach, California. Map Number 6 of 15. Maps Extending From the Mexican Border to Portuguese Point. Scale: 1:24,000.

REFERENCES
(continued)

8. U.S. Army Corps of Engineers, July 1984, Rationalizing the seismic coefficient method, Waterways Experiment Station.

9. U.S. Department of Agriculture, 1953, Stereographic Aerial Photograph Numbers AXN-8M-75 through 77, and AXN-8M-96 and 97. Flown April 1953.

10. U.S. Geological Survey, 1968 (photo revised 1973). Topographic Quadrangle, Solana Beach, California. Scale: 1:24,000.